Peter Bates

EXTERNAL PARASITES OF SMALL RUMINANTS

A Practical Guide to their Prevention and Control

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This book is dedicated to
Mark Robin Rankin
1958–2008
A great entomologist and an even greater friend

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www.cabi.org

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Preface

Initially trained as a microbiologist, I have had the privilege of working as a veterinary entomologist for over 30 years, for all of which I was employed by the Veterinary Laboratories Agency (VLA), formerly the Central Veterinary Laboratory (CVL), an executive agency of the Department for the Environment, Food and Rural Affairs (Defra), itself formerly the Ministry of Agriculture, Fisheries and Food (MAFF). During this period, I was primarily involved in research and consultancy supporting the sheep scab (*Psoroptes ovis*) eradication campaign in Great Britain. Consequently, this book is unashamedly biased towards sheep scab, together with the two other major ectoparasitic problems facing sheep production worldwide: blowfly strike and chewing lice (*Bovicola ovis*). I have wanted to write a book of this type for many years and, since leaving the VLA to set up as an independent veterinary entomology consultant, I decided that now was the time to record my accrued knowledge and experiences in the subject. Textbooks specializing in the ectoparasites of sheep are rare and those specializing in the ectoparasites of goats are even rarer. Yet ectoparasites of sheep are a major source of production loss and cause significant welfare problems throughout the world. I hope that this book will redress the issue. It is an amalgamation of lectures, presentations and workshops given to practising veterinary surgeons, veterinary and agricultural students, farmers, government extension officers and livestock advisors, both nationally and internationally. One of the primary objectives of the book was to provide a textbook suitable both as a reference book and a source of information for practising veterinary surgeons, farmers, government extension officers and livestock advisors, as well as teachers, lecturers and students in veterinary medicine, agriculture and medical and veterinary entomology. I have tried to make the subject matter relevant worldwide, not just to the extensive farming countries of Australia, Europe, New Zealand, South Africa and South America, but also to sheep and goat producers in the less developed countries. This first edition is by no means 100% complete and there are many areas where, in my opinion, more information needs to be presented. I gladly welcome any comments and criticisms, positive or negative, and (hopefully!) these will be included in future editions.

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Compiling a book of this depth requires the help of many friends and colleagues from around the world. Foremost I must acknowledge my friends and former bosses at the Central Veterinary Laboratory (CVL), Alan Kirkwood and David Tarry. Thanks for passing on to me your knowledge and enthusiasm for veterinary entomology.

Thanks too to all national and international government veterinary officers, research workers, farmers and livestock advisors I have met on my international travels, particularly in Argentina, Australia, France, the Republic of Ireland, South Africa and Uruguay. Thanks also to the organizers of the national conferences of the Sheep Veterinary Society (SVS) and the Goat Veterinary Society (GVS), and the international conferences of the World Association for the Advancement of Veterinary Parasitology (WAAVP) and the International Sheep Veterinary Society (ISVS) for their excellent networking opportunities. Another special thanks to the friends and colleagues associated with the European Union COST Action Group 833, Mange and Myiasis of Livestock. Thanks for the fantastic meetings and the equally fantastic entertainment.

A very special thanks to the following for sharing their knowledge and enthusiasm with me: Mauricio Bulman, Fermin Olachea and Antonio Romano (Argentina); Peter James, Gary Levot, John Plant, Peter Johnson and Nick Jonsson (Australia); Bertrand Losson (Belgium); Inga Stamphoj (Denmark); Ann Baker, Martin Hall, Chris Lewis and Richard Wall (England); Francis Personne and Philippe Dorchies (France); Arndt Liebisch and Hans Hammel (Germany); Elias Papadopoulos and Smaro Sotiraki (Greece); Stefania Perucci and Domenico Otranto (Italy); Robert Farkas (Hungary); Dermot O'Brian (Republic of Ireland); John Huntley, David Smith and Neil Sargison (Scotland); Set Bornstein (Sweden); Leon Fourie (Republic of South Africa); Manuela Schnyder, Peter Deplazes, Hansueli Ochs and Kurt Pfister (Switzerland); and Juan Mari and Ulysses Cuore (Uruguay). Special thanks also to Peter Heath and Dave Cole (New Zealand).

Thanks also to friends, colleagues and contacts (past and present) within the Department for the Environment, Food and Rural Affairs (Defra), the Veterinary Laboratories Agency (VLA) and Animal Health (these last two now merged to form the Animal Health and Veterinary Laboratories Agency, AHVLA) – in all their former incarnations – and similarly to friends, colleagues and contacts (past and present) within the veterinary pharmaceutical companies (and all their former incarnations) whom I had the pleasure of working with, particularly while freezing cold and wet plunge dipping sheep in the depths of a UK winter.

1

Introduction

Small Ruminants

Sheep and goats (collectively termed small ruminants – or small stock) were the first livestock to be domesticated, in central Asia, over 10,000 years ago, and are both currently widespread throughout the world. In 2005, there were 1,001,351,000 breeding sheep in the world (Table 1.1), with the largest population found in China (147,000,000) and 23,933,000 found in the UK (BWMB, 2006). According to FAO statistics, by 2007 the world breeding sheep population had increased to 1,112,520,621 and there were 850,219,925 breeding goats in 2007 (www.fao.org/corp/statistics/en), with the largest populations recorded in China (183 million) and India (120 million) (www.fao.org/ag). Within Europe, Greece has the largest number of goats (5 million), followed by Spain (3 million) and France (1 million). In the UK, there are approximately 98,000 goats (Harwood, 2008).

Sheep and goats are cloven-hooved animals belonging to the order Artiodactyla and are typical ruminants, possessing a four-chambered stomach and able to 'chew the cud' (ruminate); they belong within the suborder Ruminantia, the family Bovidae, the subfamily Caprinae and to the genera *Ovis* (sheep) or *Capra* (goat). The domestic sheep is *Ovis aries* and the domestic goat *Capra hircus*.

It is not always easy to distinguish sheep from goats, and there is at least one intermediate group, the genus *Ammotragus*, containing the barbary 'sheep' of North Africa (*Ammotragus lervia*) (Ryder and Stephenson, 1968). Sheep and goats both depend on forage as their major food source; however, in the wild they occupy different ecological niches. Goats are found in more inhospitable areas, browsing on a mixed flora of bushes and shrubs and poor grass. Sheep mainly graze on lusher pastures but may also browse on the young shoots of bushes and trees.

Ryder and Stephenson (1968) describe a number of phenotypic differences that can be used to distinguish sheep from goats. In general, goats often have beards and have more slender horns than sheep. Other distinguishing features include small skeletal differences that are not immediately visually obvious. Sheep have face or tear glands in front of the eyes (the infra-orbital fossae), and foot or scent 'glands' between the hooves (the interdigital fossae). These are both lacking in goats, although goats may have small 'glands' in their forefeet. Male goats, in contrast, can have glands beneath the tail, which are not present in sheep. Sheep and goats can also be distinguished genotypically. The chromosome number of domestic sheep (*O. aries*) being 54, and that

Table 1.1. World breeding sheep populations 2005 (Source: BWMB, 2006).

Country	Population
China	147,000,000
Australia	102,620,000
India	57,900,000
(Former) USSR	54,600,000
Iran	53,000,000
Sudan	42,800,000
New Zealand	40,188,000
South Africa	25,316,000
Turkey	25,000,000
Pakistan	24,700,000
UK	23,933,000
Total (inc. other countries)	1,001,351,000

of goats (*C. hircus*) 60, successful cross-breeding is unlikely (Davies, 2007).

The interdigital fossae of sheep consist of an invagination of skin which forms a pouch opening near the top of the cleft between the two toes. The lining of the pouch bears short wool fibres with sebaceous glands, and well-developed sweat glands (Ryder and Stephenson, 1968). The function of the foot glands is thought to be the production of a scent which, when deposited on the ground or grass, helps the flocking behaviour of sheep. Flocking behaviour is highly developed in sheep and this, along with their docility, has helped in their domestication and management (Ryder and Stephenson, 1968). Domestic sheep vary greatly in their flock behaviour, from the closely packed 'mobs' of grazing merinos, to the almost solitary roving of the British mountain sheep, such as the Scottish Blackface (Ryder and Stephenson, 1968).

On a global scale, sheep found in tropical regions have adapted to the hot climate and the problem of heat dissipation by having hair (not wool) and a stored energy source (in the form of fat) in the tail. Large numbers of fat-tailed sheep are found in Africa, the Middle East and most African countries. In Europe, sheep have adapted to live in cold, wet inhospitable regions through the development of a thick subcutaneous fat layer and large deposits of internal fat. Adults have mainly carpet quality wool, and the young are born with a thick felt-like birth coat that allows them to survive wet and cold conditions (Davies, 2007).

The role of sheep and goats in different societies varies; much of this variation is based around religious and cultural beliefs, which sometimes prohibit the eating of certain meats and so, by definition, place increased importance on other species of meat animal. Islam forbids the eating of any pig meat, and although there is no prohibition on the eating of beef and beef products, sheep and goat meat is consumed primarily. Similarly, the eating of pig meat is forbidden under Judaic law. Middle Eastern Christians are not prohibited by their religion from eating pork or beef, but through custom and tradition tend to favour sheep or goat meat. The type of sheep (or goat) required varies with the occasion. For example, on religious holidays – such as Eid al-Adha among Muslims and Easter among Greek/Middle Eastern Christians – an entire small lamb (or goat) is required. The eating of sheep or goat meat is not just confined to religious festivals. For many, it is the primary staple meat for everyday life and, as such, there is a constant demand for it.

Sheep and Goat Production

Sheep and goats are primarily kept for milk, meat, fibre, leather and showing, or as pets. Many sheep and goats are also used as management tools in land conservation projects for maintaining environmentally sensitive areas.

Meat

Goat meat is the most widely consumed meat in the world because there are few religious taboos relating to it (Harwood, 2008) and it has a valuable by-product: fibre (cashmere and mohair). Areas where goat meat is readily eaten include the West Indies, parts of Africa (Burundi, Rwanda, Malawi, Sudan, Ghana and East Africa), India, Sri Lanka, Malaysia and the Philippines. Australia and New Zealand regularly export feral goat

meat. Between 1977 and 1978 Australia exported 3684t of goat meat and New Zealand 1220t. Importers included the Caribbean and Fiji (from New Zealand) and the Caribbean, Middle East, Malaysia, Japan and Canada (from Australia) (Devendra and Burns, 1983).

Goat meat has a distinctive flavour and demands high prices (Devendra and Burns, 1983); it is considered preferable to lamb or mutton. In sheep, the fat is distributed throughout the body, whereas visceral fat is characteristic of goat meat and is responsible for its tenderness and succulence. Weight for weight goat meat has a higher lean content than mutton.

There are three types of goat meat (Devendra and Burns, 1983):

1. Meat from kids (8–12 weeks old, 6–8 kg). This is mainly confined to Latin America and the West Indies and is also known as 'cabrilo'.
2. Meat from young goats (1–2 years old). This is the most popular, with live weights ranging from 13 to 25 kg (males) and from 11–20 kg (females).
3. Meat from old goats (2–6 years old). This is tougher and less acceptable.

For sheep, the main meat product is lamb, defined as the meat from animals slaughtered up to 1 year of age. Mutton is the product from older animals, including both male and female culls from the breeding flock. In most countries, mutton makes a small contribution to the total production and is generally used in meat processing. It is in the temperate grassland zones of both the northern and southern hemispheres that there is the greatest emphasis on sheep meat production associated with the most intensive systems, highest stocking rates and the most productive breeds and crossbreeds (Davies, 2007).

Consumption of lamb is influenced by tradition and is related to the size of the sheep population of the country. In the European Union (EU), it varies from 14 kg per person for Greece to 6.3 kg per person for the UK; it is only 1.2 kg per person in Germany (http://epp.eurostat.ec.europa.eu/). There is a considerable amount of trade within Europe and New Zealand and Australia. The latter are major exporters to a number of South-east Asian and Middle Eastern countries, but more than 50% of both lamb and mutton from the main exporter, New Zealand, comes to Europe.

Currently, New Zealand has a tariff-free entitlement to export the carcass weight equivalent of 227,000t of sheep meat to the EU, with approximately 17% going to Germany, 14% to France and 42% to the UK. Historically, all New Zealand lamb was frozen and filled a deficit in supply from home production during the early months of the year. The UK is now almost self-sufficient in lamb, exporting approximately 77,000t to and importing 8000 t of lamb from other EU countries (Davies, 2007).

Milk and milk products

The nutritive value of ewes' milk is superior to that of cows' milk (Table 1.2). Ewes are a local source of milk for human consumption in many poor communities, but it is mainly in the flocks of the European countries that border the Mediterranean and in some areas

Table 1.2. Relative nutritional values of sheep, goat and cow milk (data from Mills, 1989).

Value	Sheep	Goat	Cow
Energy[a]	102	71	65
Fat[b]	7.8	3.9	3.5
Protein[b]	5.6	3.3	3.3
Lactose[b]	4.7	4.4	4.6
Minerals[b]	0.87	0.80	0.75
Vitamin A[c]	83	44	52
β-Carotene[c]	0.2	<0.1	21
Vitamin D[c]	0.18[d]–0.88[e]	0.12	0.03
Vitamin E[c]	120	30	90
Vitamin C[c]	4700	1100	1500
Thiamine[c]	85	41	40
Riboflavin[c]	330	138	180
Vitamin B_6[c]	83	63	50
Vitamin B_{12}[c]	0.6	0.08	0.4
Nicotinic acid[c]	428	328	80
Pantothenic acid[c]	464	415	50
Biotin[c]	2.6	3.1	3.0
Folic acid[c]	5.6	0.6	5.0

[a]kcal; [b]%; [c]μg/100 g; [d]summer; [e]winter.

of south-west Asia that milk and milk products are a major output of the sheep flock (Davies, 2007). Large numbers of ewes are kept for milk production in southern Europe, particularly in Greece, Italy, Spain, France and Portugal, with most of the milk manufactured into cheese or yoghurt.

Over 80% of French milking ewes are found in the Roquefort area, in the south-east of the Dordogne region, with the remaining milking ewes found in the Pyrenees and Corsica. In the Roquefort area, the local Lacaune breed provides milk for the production of the famous Roquefort cheese (Davies, 2007); the lambs of this breed are raised for meat and replacement stock. In the western Pyrenees, the Basco-Béarnaise and Manech breeds provide over 50% of their revenue from milk, 40% from meat and 10% from wool. The ewes are lambed in the foothills in mid-winter and the lambs sold for the Easter trade (March/April). The ewes are driven up to the high mountain pastures as soon as the snow has melted, a process known as transhumance. Ewes' milk cheese has been made in Italy since before the Roman Empire. Sheep are mainly milked in the south of the country and on the islands of Sicily and Sardinia. The principal milking breeds include the Comisano and the Sarde. Sicily is more dependent on milking than mainland Italy, primarily owing to the lack of water; it produces Pecorino cheese and Ricotta cheese as a traditional by-product. In Greece and Cyprus, sheep milk is processed into feta and halloumi cheese, respectively, as well as into yoghurt and butter. Israel depends largely on sheep and goats, cattle being expensive to feed and having to be housed most of the year. The Awassi, a fat-tailed sheep, is the main breed, recently crossed with the Friesland to form a new breed, the Assaf. Sheep are also extensively milked in Turkey, Iran, Iraq, Saudi Arabia, Syria, Romania, Poland and the Balkans.

Milk production can give very good financial returns, but labour costs are high and provision has to be made for the rearing of lambs. This is achieved in small-scale low-cost systems by separating ewes and lambs for part of the day, and in larger scale operations by completely removing the lambs from their mothers either soon after birth, or at 6 weeks of age, and then feeding them an appropriate artificial diet (Davies, 2007). The Friesland sheep breed is considered to be the highest yielding breed in the world and has been found to improve the yield of any breed it is mated with.

One-third of the world's goat population is kept in South-east Asia (India, Pakistan and Malaysia), mainly for the production of milk and milk products, with meat (and leather) as by-products of milking. Other countries where goats are regularly milked include Brazil, Cyprus, Egypt, Iran, Israel, Niger, Nigeria, South Africa, Sudan, Turkey and Venezuela (Devendra and Burns, 1983).

Milk, yoghurt and cheese from sheep and goats are now gaining in popularity in the Western world, particularly for consumers who are allergic to milk and dairy products of bovine origin.

Fibre

The coat fibres of many mammals can be harvested for textile use, and fibres produced by sheep or goats include wool, common goat hair (CGH), mohair, cashmere (pashmina) and caprine fine fibre (CFF) (Table 1.3).

Wool

Wool, like hair, hoof and horn, is made from the modified protein keratin. Although originating as an under wool of wild sheep, the range of fleece types seen on sheep breeds today have been developed by selective breeding. After the domestication of sheep, the value of wool as a clothing fibre gave it a unique role in human history; it has been vitally important in the economies of countries ranging from ancient Mesopotamia, through Greece and Rome, to medieval England and modern Australia (Ryder, 1994). Other animals can provide meat and milk, but only with the sheep has the use of the coat in textiles become so highly developed (Ryder, 1983).

In primitive sheep, the coat cover includes hair and a soft, downy undercoat.

Table 1.3. Animal hairs used in textiles (data from Devendra and Burns, 1983).

Fibre	Producing countries	Fineness (μm)	Length (cm)
Mohair	Turkey, South Africa, USA, (former) USSR	24–45	10–25
Cashmere	India, Tibet, China, Iran, (former) USSR	15–19	2–8
Camel	China, Mongolia, (former) USSR	16–25	3–5 (fine) 13–25 (coarse)
Alpaca	Peru, Bolivia	27–45	20–23
Vicuna	Peru	13	2–5
Llama	Peru	30–60	13–25
¾ Angora cross	Rahuri, India (average)	20	10.5
Pashmina × Gaddi	Mukteswar, India (average)	13	5.0
Wool (merino)	(For comparison)	17–25	6–12

Sheep breeds that have evolved in tropical areas have hair and not wool, and moult annually. Wool is the inherent fibre coat of sheep of temperate and cold climates, and has been harvested and used for garment and carpet making for centuries. Despite the advent of synthetic fibres, it remains a commodity that is still traded internationally (Davies, 2007). In 2005, some 1,200,581t of raw wool was produced worldwide (Table 1.4), with Australia the main producer (BWMB, 2006).

In processed wool, the tiny overlapping fibre scales allow the wool fibres to repel spilled liquids with ease. The natural crimp allows fibres to retain their shape, and wool fibres can be stretched and then readily bounce back into shape. Wool readily accepts dye. It also has excellent insulation and water-repellent qualities, and provides the sheep with the necessary protection from excessive cold and wet winter conditions. Most breeds (with the exception of breeds such as the South African Dorper and the British Wiltshire Horn) do not moult and the fleece has to be removed annually by shearing. In the UK, the contribution of wool to the income of a sheep farm has diminished considerably since the development of synthetic fibres. Presently, the cost of shearing relative to the value of the fleece often leaves little or no profit margin.

China, with its rapidly expanding textile industry, has become the major importer of top-quality wool from most of the main producing countries, including 45% of the total and 70% of the fine and superfine Australian clip, 50% of the medium quality

Table 1.4. World production of raw wool, 2005 (Source: BWMB, 2006).

Country	Wool production (t)
Australia	326,193
New Zealand	174,971
China	167,757
(Former) USSR	79,575
India	38,080
Uruguay	29,396
UK	28,647
South Africa	28,024
Turkey	27,000
Argentina	25,329
World total (inc. other countries)	1,200,581

export of Uruguay and the greatest part of the slightly coarser New Zealand export (Davies, 2007). Nutrition has an important influence on wool growth and high nutritional demands at pregnancy result in reduced fleece weights. Conversely, undernutrition will give rise to finer fibres. In practical circumstances, a balance has to be achieved between the effect of the above on incomes via meat and via wool production.

The value of wool can vary considerably depending on its weight and quality. The former is determined by the staple length and the density, fineness and crimp of the fibres. Some of the UK Longwool breeds claim yields up to 10kg compared with an average of approximately 2.5kg for lowland breeds and 2.0kg for some hill breeds. Hill breeds tend to produce course wools with a staple diameter of 35–50μm; this is used mainly for carpet or rug making.

Most lowland breeds produce a better-quality finer fibre with a staple diameter of 24–33 µm, which used for hosiery and knitwear. The merino produces a heavy fleece of 5–12 kg with a staple diameter less than 24 µm which is used in the manufacture of high-quality garments (www.wool.com).

The best quality fine wool production is mainly centred on the merino and Romney breeds. Dry, arid subtropical areas are particularly well suited to this type of production because although the poor quality of the diet reduces the wool yield, it also results in an increase in the fineness of the staple. Large populations of these sheep exist in Australia and South Africa, and in Argentina and Uruguay, though the decline in wool value in the past few decades has seen a substantial decrease in numbers and a move to meat production in many of the better land areas of these countries (Davies, 2007).

Apart from use in the production of clothing and carpets, wool can also be used as house insulation (e.g. Thermafleece™). Wool's ability to rapidly adsorb and release water vapour has demonstrated that wool insulation can help to keep buildings cool in summer and warm in winter.

Common goat hair

A by-product of goat meat or dairy production, goat hair is a valuable commodity. Common goat hair (CGH) is a cheap fibre, but mohair and cashmere (see next two sections) are speciality fibres of high price per unit weight.

CGH is used mainly for the manufacture of cheap felts and carpets for the automobile industry. In the clothing trade, small quantities are still used in making interlinings despite competition from synthetic fibres. White beard hairs are sometimes used as substitutes for kemp for fancy effects in ladies outerwear such as tweeds (Devendra and Burns, 1983). CGH mainly comes from tropical Asia and the Middle East, but is also an important product in Africa and Argentina. Pakistan is the largest single exporter and has defined official grades, as well as three colour grades (White, Grey and Black), within each of which the hair is graded by length as follows (Devendra and Burns, 1983):

1. PAK Extra Long: average fibre length 3.5 inches (9 cm), with less than 10% of short (2 inches/5 cm or less) fibres.
2. PAK Long: length 2.0–3.5 inches (5–9 cm), with less than 25% short fibres.
3. PAK Short: fibres 2 inches (5 cm) or less in length.

All export grades must contain more than 80% of clean hair and less than 3% vegetable matter. Devendra and Burns (1983) recorded that Pakistan's annual production of CGH was about 3500 t, of which 80% was clipped and 20% taken from skins. As long hair is more valuable than short hair, as well as providing a greater weight per goat, the demands of the hair trade conflict with those of the fine leather trade, for which short-haired goats provide the best skins (Devendra and Burns, 1983).

Mohair

Mohair is the fleece from an angora goat. The word mohair was adopted into English before 1570 from the Arabic 'mukhayyar', a type of haircloth. Good-quality mohair is soft to touch, and firm and bright; it forms wavy, twisted and solid ringlets of uniform size all over the body (Devendra and Burns, 1983). Mohair grows in lustrous white locks, with the most desirable type curling in ringlets, while other types grow in flat waves. The growth of the fibre approximates 2.0–3.0 cm/month.

The length of commercial mohair ranges from 10 to 25 cm, with an average of 15 cm. In contrast to wool or cashmere, the surface scale structure of mohair is very smooth, giving it lustre, a soft handle and a resistance to felting. Processed mohair is less 'itchy' than wool, primarily as a result of this scale pattern. The tip of the mohair staple is blunt, and evenness of length over the whole fleece is the ideal, because this largely determines the commercial usefulness of the fibre. Fineness is the

most important character of mohair, as the quality of the manufactured material depends on this. Mohair is notable for its high lustre and sheen, and is often used in fibre blends to add these qualities to other textiles.

The world production of mohair is approximately 5 million kg/year, with South Africa, Turkey, Lesotho, the USA and Argentina the main producers. South Africa currently produces more than 60% of total world production of mohair. In 2004, mohair production in the three major producing states of the USA (Arizona, New Mexico and Texas) was 1.79 million pounds (0.8 million kg), with 242,000 goats and kids clipped. The average weight of the clip was 7.4 pounds (3.3 kg), with a value of US$3.59 million, up 15% from 2003 (Anon, 2005). In the UK, there are approximately 6000 angora goats, producing 20–25 t mohair/year (Mason, 2008), of which approximately 10 t is used by producers and the rest sold to home spinners (CALU, 2005). Recent UK prices for mohair were £5.50/kg for kid mohair and £1.65/kg for adult mohair (CALU, 2005; Mason, 2008).

Angora goats are generally shorn twice a year, in spring and autumn. The mean fibre diameter ranges from 23 µm at the first shearing to as much as 38 µm in older animals. The fleece weight of mohair also increases with age. Males produce an average 2.6 kg in their first year and an average of 4.4 kg when 4 years old. Females produce slightly less, 2.8 kg in their first year and 3.7 kg when 4 years old. Kid mohair, which is the finest, is therefore the most costly. Fibre production tends to decline after 5 years of age and breeding stock is normally culled at around 6 years old (Devendra and Burns, 1983).

Mohair from young goats (kid mohair) is used in knitwear; from goats of an intermediate age it is used in suiting materials; the stronger 'fine hair' types are used in coating and rug manufacture. The market for mohair is affected by the fashion industry and the world prices are subject to large fluctuations. Currently, Britain processes 60% of the world's mohair, almost all of which is imported (CALU, 2005).

Cashmere (pashmina) and caprine fine fibre (CFF)

All goats (with the exception of angora goats) produce two coat fibres: an outer, coarse coat of guard hairs and a second fine, downy undercoat that grows and is shed seasonally. Cashmere is the valuable fine undercoat, for winter protection, and found in varying degrees on all goats, but in quantities that are too small and lengths that are too short for commercial use. Most dairy breeders (particularly those who show their goats) regard it as undesirable, as it spoils the appearance of the goat's coat. Cashmere is usually referred to as 'down', and sometimes as wool. Goats that produce it are sometimes referred to as 'down breeds', e.g. the Don down goat of the (former) USSR. The best cashmere is white, but supplies of fawn to grey down are more plentiful. Cashmere clothing is exceptionally light, soft and warm, and is therefore in the luxury class. The small quantity yielded per animal (approximately 100 g) makes the raw material costly, and the special processing that is required adds to the value of the finished article (Devendra and Burns, 1983).

Cashmere is weaker than wool but is luxurious, with an extraordinary soft and resilient fibre that is receptive to dyes. It is used chiefly for speciality ladies' clothing, sweaters, scarves, stoles, etc. The demand for cashmere garments is strong, particularly in Western Europe, the USA and Japan, and is less affected by fashion trends. Consequently, the price for cashmere is more stable than that of mohair (CALU, 2005). It is also blended with wool in felt making, although cashmere has very little felting tendency on its own. More than 3000 t of cashmere are produced worldwide (SAC, 2008), the majority coming from Mongolia and smaller amounts from Afghanistan, Australia, India, Iran, Nepal, New Zealand, Pakistan and Tibet. There are currently around 50 cashmere producers in the UK with a national herd of around 2,500 goats (SAC, 2008). The major buyers of cashmere are the USA, UK and Japan.

The fibres of cashmere average 2.5 cm in length and about 15 µm (12–18 µm) in diameter. Feral goats and many dairy goats produce the finest cashmere (diameter 16 µm or less) but because of the lengths and weight (around 50–70 g) it is generally unusable. However, once these goats are crossed with higher weight/volume producing goats, new breeds of good cashmere producers with increased quantity of production can be obtained. The improved 'Macauley Institute' strain can produce 200 g of cashmere/year, with a value of £16.5 raw or £40 when processed into yarn (Mason, 2008). In the UK, there are currently approximately 250–400 Macauley strain goats and 2000 feral goats producing cashmere (Mason, 2008).

Cashmere growth is generally regarded as being triggered by the shortening day length of late summer/autumn, although other factors such as temperature and even diet may influence production. The coat generally continues to grow until the end of the year in preparation for the coldest weather, and is removed in the early to late spring depending on the method of harvesting. Where facilities allow, the goats can be shorn in early March and kept indoors for several weeks before being allowed back out. This ensures that the maximum amount of cashmere is obtained from each goat as shearing is done before the coat loosens naturally and falls out. Where facilities to house the goats do not exist, it is more common to comb or in some cases pluck out the fibre. This has the disadvantage of having to be done after the coat has begun to loosen and therefore much of the fibre can be lost, but it has the advantage of leaving the main coat, or guard hair, intact, thus allowing the goat to continue to have some protection against the elements. This method also spreads the process out over a much longer period because the goats shed at different times and two or three operations are usually required to remove all the cashmere. Combed or plucked cashmere does not have cut ends, but has shed (brush) proximal ends, and pointed intact or broken tips. Some coarse (outer coat) hairs usually remain among commercial cashmere fibres, and many samples contain pigmented fibres. The surface scales of cashmere fibres protrude like those of wool fibres, but the scales are longer (Devendra and Burns, 1983).

Fleeces are individually graded into the categories of white hosiery, white weaving, coloured hosiery, coloured weaving and reject. Hosiery (white or coloured) grade cashmere is internationally agreed as having fibres of below 15.5 µm diameter and possessing the characteristics of cashmere. Weaving (white or coloured) grade has fibres of diameter above 15.5 µm but below 18.5 µm, and still retains the characteristics of cashmere. Reject grade fleeces (which become CFF) either have fibres outside the diameter parameters or do not have the true characteristics of cashmere. This can be caused by a number of factors and is fairly subjective on the part of the grader. Because of the very strict adherence to the definition, particularly in the USA, erring on the side of caution tends to predominate.

Scotland processes over 1000 t of imported cashmere (60% of the world production) each year (CALU, 2005). Recent prices for cashmere are £90/kg for fibres of below diameter 16.5 µm and £70/kg for those of diameter 16.5–18.5 µm (CALU, 2005).

Lanolin

Lanolin (wool grease) is a greasy yellow substance secreted by the sebaceous glands that gives fleece its waterproofing and weather protection properties. Certain breeds of sheep produce large amounts of lanolin. Lanolin has antifungal and antibacterial properties, and protects the sheep/goat skin from infection.

The similarity of lanolin to many oils produced by the human skin has allowed it to be widely used in the pharmaceutical industry. When mixed with suitable vegetable oils or soft paraffin, the resulting cream is excellent at penetrating the skin and can be used as a 'carrier' to deliver pharmaceutical drugs subcutaneously. As well as being used as a base for ointments and creams, lanolin is also used as a lubricant in the

finishing and preserving of leather. Lanolin is also used on oil rigs to prevent corrosion; similarly, it is used to protect motor car parts in storage.

Leather

Leather forms a very useful by-product of goat production in several countries. In particular, there is a significant export trade in skins from India and Pakistan, and from several African countries, notably Morocco, Somalia, Uganda and Nigeria (Devendra and Burns, 1983). The most valuable goat skins, in terms of price per unit weight, are those that are most suitable for the production of first quality 'glazed kid' leather. Such skins must be strong and sound, although thin and light in weight. Coarser skins of sound quality are also in demand for the manufacture of strong footwear; being heavier, these may command an equal price per goat although they have less per unit weight (Devendra and Burns, 1983).

A unique form of sheep pelt is astrakhan, taken from the karakul sheep (*Ovis aries platyura*). Karakul sheep (IFTF, 2011) are believed to be one of the oldest breeds of domestic sheep. Originally from the steppes of Turkistan, this fat-tailed sheep gradually spread to other regions of Central Asia. Today, karakul sheep are predominantly farmed in Afghanistan, the Central Asian republics of the former USSR and Namibia. Karakul sheep have been bred in Namibia since 1900 and now enjoy the brand name Swakara (South West African Karakul). Karakul sheep are able to survive the harsh, arid conditions of these regions, while providing both a source of food and income for local people. Because of the harsh climatic conditions, only a small proportion of newborn lambs (20–30% depending on the region and severity of weather) can be kept and raised to maturity without damaging the land with overgrazing. In Namibia, 3–12 ha of land are needed to graze each sheep. Young lambs that cannot be sustained naturally are slaughtered shortly after birth, and produce meat and the soft, lustrous, predominantly black, karakul lamb pelt (astrakhan). The prices that are achieved at international auctions for karakul pelts help producers to earn hard currency in regions that offer little, if any, alternative sources of income. Karakul sheep can breed out of season and produce young three times in 2 years. Single lambs are the rule, but occasionally twins are born. Karakul lambskins are typically used for full fur garments, such as coats and skirts, and as trimming, edging and lining, and for accessories.

External Parasites of Sheep and Goats

Small ruminants can be affected with a number of parasites that inhabit their skin or fleece (ectoparasites), and can seriously affect their productive ability, resulting in reduced milk and meat yields, the downgrading of wool and leather quality, and requirements for expensive control programmes. More importantly, ectoparasites can adversely affect the welfare of infested animals. In the UK, it is the legal responsibility of flock owners to prevent or cure infestations within their flocks. Failure to do so can result in a prosecution for animal cruelty, with a potential heavy fine or even a prison sentence.

All ectoparasites of small ruminants belong to the Phylum Arthropoda ('jointed legs') and specifically to the Orders Arachnida and Insecta. Ectoparasites can be divided into two broad groups: (i) permanent (resident) ectoparasites that spend their entire life cycle on the host; and (ii) semi-permanent ectoparasites, which possess a life cycle with at least one stage that is free living away from the host (Table 1.5).

The Skin Environment

The skin of the sheep or goat is where ectoparasites live, obtain their food and, in the case of permanent ectoparasites, reproduce. In order to study the biology and control of sheep/goat ectoparasites it is therefore necessary to understand the skin environment on which they depend. This skin environment

Table 1.5. Sheep and goat ectoparasites.

Permanent (resident) ectoparasites	Semi-permanent ectoparasites
Mange mites (*Chorioptes*, *Demodex*, *Psorobia*, *Psoroptes*, *Sarcoptes*)	Harvest mites[a] (Trombiculidae)
Ear mites (*Psoroptes*, *Raillietia*)	Soft ticks[b] (Argasidae: *Ornithodoros*, *Otobius*)
Chewing lice (*Bovicola*)	Hard ticks[b] (Ixodidae: *Amblyomma*, *Hyalloma*, *Ixodes*, *Rhipicephalus*, *Boophilus*, *Dermacenor*, *Haemophysalis*)
Sucking Lice (*Linognathus*)	Facultative myiasis flies[a] (*Lucilia*, *Calliphora*, *Chrysomya*)
Keds (*Melophagus*)	Obligate myiasis flies[a] (*Wohlfahrtia*, *Oestrus*, *Przhevalskiana*, *Dermatobia*, *Callitroga*)
	Blood-sucking/secretophagous flies[c] (*Culicoides*, *Hydrotea*)
	Fleas[c] (*Ctenocephalides*)

[a]Parasitic in the larval stage; [b]all stages parasitic but spend long periods off the host; [c]adults parasitic.

must provide the parasite with its optimal temperature, humidity, food source and protection. The skin is also the major target area for the chemical control of ectoparasites through the use of specifically formulated pesticides (ectoparasiticides). Ectoparasiticide formulations are designed either to be absorbed directly on to the skin or hair grease through direct topical administration, when they kill ectoparasites by contact (contact ectoparasiticides), or through a systemic action via secretions into the skin or hair grease which kill the ectoparasites as they feed (systemic ectoparasiticides).

Like all other mammals the skin of sheep and goats consists of a 'dead' outer cornified stratum corneum, an uncornified 'living' epidermis and a dermis. The skin surface of sheep (and goats) consists of roughly hexagonal squama punctuated by hair or wool fibres and their associated follicle pores (Pitman and Rostas, 1981). Some species of mange mite (e.g. *Sarcoptes scabiei*), burrow into the stratum corneum and feed on the germinal layer of the epidermis. Other species of mange mite (e.g. *Psorobia ovis*) live and feed in cavities under the stratum corneum.

There are two types of follicle: primary follicles produce hair or kemp, whereas secondary follicles produce finer fibre or wool. Primary follicles consist of a sebaceous gland, a sweat gland and an erector pili muscle. Secondary follicles only have associated sebaceous glands. Follicles and their associated sebaceous glands are the sites of infestation by *Demodex* spp. mites, which feed on the epidermis. Larvae of *S. scabiei* 'shelter' in the hair follicles before moulting into the nymphal stage and burrowing into the stratum corneum.

The hair and wool follicles in sheep and, consequently, the hair and wool fibres too, are not randomly distributed over the body but are in definite groups containing one to five primary follicles and a number of secondary follicles. Hair and wool follicle densities and types of fibres vary considerably with region of the sheep's body examined. The body can generally be divided into wool-growing regions and hair-growing regions. The wool-growing regions include the mid-side, mid-flank and flank. The hair-growing regions include the inguinal junction, the inguinum, axilla, scrotum, chin, nose and pinna (Pitman and Rostas, 1981). The epidermis is thinner on wool-growing areas (30 mm) than in hair-growing areas (500 mm). Similarly, while there is an area of uniform skin thickness in

the middle of the sheep's back on either side of and parallel to the vertebral column, there is also a steep dorsoventral gradient in skin thickness on either side of the medial dorsal line. The thicker skin is over the vertebral column, near the tail along the back and towards the neck in older sheep (Pitman and Rostas, 1981). Merino sheep are reported to have 300–400 primary follicles/cm^2 and 6000–10000 secondary follicles/cm^2 in wool-growing areas of the body. The average density of primary follicles does not change appreciably on the hair-growing areas, but the densities of the secondary follicles are markedly reduced.

The wool fibres seen in modern sheep hang together in locks known as 'staples', and different fleece types have varying proportions of different fibre types. The wild ancestor to modern sheep (the mouflon, *Ovis musimon*) has a brown double coat, in which thick, bristly kemp hairs obscure a shorter, very fine, woolly undercoat. Since domestication, sheep have been selectively bred for a finer outer coat, which has been accompanied by a coarsening of the underwool ('kemp') (Ryder, 1994). Out of this selective breeding, four types of fleece were developed: (i) fine wool (unique to the merino breed); (ii) semi-fine, short wool (English down breeds); (iii) medium type; and (iv) hairy type (e.g. Scottish Blackface). In the latter type most of the short, moulting kemps of the primitive hairy fleece have changed into long, continuously growing hairs. The base of the fibre coat, close to the skin, is the preferred habitat for species of chewing louse (*Bovicola* spp.), feeding on loose scurf (epithelial debris, wax and suint) and emulsion covering the wool fibres.

The sebaceous glands produce sebum and the sweat glands produce suint. Suint is a hygroscopic mixture of potassium salts and organic acids (oleic acid and stearic acid), and inorganic salts such as carbonates, chlorides, phosphates and sulfates of calcium, sodium, potassium and magnesium. The presence of potassium makes suint a natural detergent. The entire stratum corneum of the sheep is permeated by sweat/sebum emulsion and an intact film of the emulsion, approximately 0.90×10^{-2} mm thick, covers its outer surface. This emulsion is formed in the follicle infundibula, into which secretions of suint from the sweat glands and sebum from the sebaceous glands are emptied. Wool fibres appear to have an almost continuous coat of this emulsion (often referred to as 'yolk'). The chemical components of the emulsion vary both from animal to animal and with such factors as time of year and climate, but most lipids in the emulsion arise from the secretions of the sebaceous glands. Minor components are likely to arise from desquamating squama (i.e. keratin, cell debris, bacterial excreta and blood). Mites of the genera *Chorioptes* and *Psoroptes* actively live and feed on this emulsion layer. The hair bulb, the sebaceous gland, the sweat gland and especially the hair follicles are richly supplied with blood. These blood vessels permeate the dermis as well.

There is also a wide diversity of bacteria inhabiting the skin surface, follicles and the fibres/wool. Lyness *et al.* (1994) examined the skin/wool flora of Australian merinos and found that *Bacillus cereus* was always isolated and that *Bacillus thuringiensis* and *Pseudomonas* spp. were frequently isolated. Organisms in the *Bacillus cereus* group (including *B. thuringiensis*) form a series of characteristic protein inclusions adjacent to the endospore (insecticidal crystal proteins or ICPs) that are toxic to certain species of arthropod. Investigations into the entomotoxicity of the bacterial flora of sheep skin may highlight potential control strategies against ectoparasites. The skin bacteria may have profound effects on the epidemiology of ectoparasites. They may be responsible for variations in susceptibility between individual sheep, with ectoparasites having to adapt to differences in skin flora between hosts; those that cannot adapt to the new flora may be unable to initiate infestations. Similarly, the skin bacterial flora may be significant in relation to host specificity; the bacterial flora on a sheep may be different to that on goats and thus inhibitory to ectoparasite colonization (Bates, 2003). Skin bacteria have been found to be an important part of the diet of the sheep chewing louse *Bovicola ovis* too (Murray and Edwards, 1987).

Small ruminants are warm blooded (homeothermic) mammals, and therefore a healthy sheep or goat can maintain its body temperature within a relatively narrow range, with the hair/wool coat holding in body heat and insulating against ambient temperatures, both hot and cold. The hair/wool coat also maintains the relative humidity at skin level. There are, however, distinct differences in skin temperature depending on the body site measured (Table 1.6); temperatures range from as low as 18.8°C on the tail to 39.3°C in the inguinum (Bates, unpublished data). The temperature of sheep or goat skin is influenced by ambient temperature, radiation, convection, evaporation, shivering and exercise. The temperature of the skin of sheep has been recorded to vary from 31.0 to 38.5°C when the ambient temperature varied from 38.2 to 40.2°C. The optimal environment for the sheep chewing louse (*B. ovis*) to reproduce is a temperature of 37.0°C and a relative humidity of 70–90%. *B. ovis* is susceptible to extremes in temperature and humidity and the lice move up and down the wool fibre to accommodate changes. On hot days, the fleece temperature on exposed parts of a sheep with a fleece length of below 25 mm can range from 45°C near the skin to 65°C at the wool tip.

Table 1.6. Variations in sheep body temperature.

Location	Mean temp. (°C)	Range (°C)
Inguinum	36.0	33.7–39.3
Axillae	35.8	33.8–38.2
External auditory canal	34.0	30.6–38.2
Infra-orbital fossae	33.8	30.5–37.6
Outer pinna	32.2	28.6–35.8
Under tail-head	31.9	28.9–34.9
Inner pinna	31.7	27.2–35.1
Umbilical area	31.7	22.7–36.9
Lower venter	30.9	22.4–33.3
Poll	29.7	28.0–31.3[a]
Flanks	29.5	23.2–35.6
Crutch	29.4	26.3–36.4
Tail-head	29.1	24.9–32.8
Sternum	28.8	24.5–32.9
Withers	28.3	22.0–35.8
Tuber coxae	28.3	24.6–34.6
Brisket	27.8	24.1–37.6
Mid-back	27.7	26.1–31.0
Rump	27.7	24.7–30.0
Neck	27.4	23.4–33.5
Perineum	26.7	23.5–29.6
Tail	20.5	18.8–23.4

[a]Depends on breed.

Temperature changes can influence skin permeability by changing the activity of the sweat glands and the composition of their secretions. The results of these changes are expressed as changes in the volume, composition and viscosity of the skin emulsion, and in the degree of skin hydration (Pitman and Rostas, 1981). This latter factor may profoundly affect the aqueous content and viscosity of the emulsion because heat has only a minor effect on the output or composition of sebum unless it is prolonged for over 3 days. In addition to the higher output of sebum when high temperatures are maintained for long periods, the relative concentrations of linoleic acid (and other free fatty acids) in the sebum increase. In cattle, the skin surface temperature in the shade does not vary appreciably from one area of the body to another. However, the coat type and skin colour are important if cattle are in the sunlight. An 8°C temperature difference has been reported between black-haired (heat-absorbing) and white-haired (heat-reflecting) regions of cattle. It is possible that these differences may also hold true for short-haired goats.

Moulting in mammals is a means of not only replacing the worn-out skin structures and hair, but of providing the animal with coats suitable for the heat of summer and the cold of winter. The replacement of the fibre coat before the old one has shed occurs in wild sheep and seems to be designed to ensure that the animal will at no time be naked as a result of the moult (Ryder and Stephenson, 1968). True moulting can still be seen in some breeds of domestic sheep (e.g. Soay and Shetland), and the majority of other breeds still have a tendency to shed a proportion of their fibre seasonally, but moulting is not evident in some breeds (e.g. the merino) and the wool is said to grow continuously. Moulting in goats is similar to that in wild sheep (mouflon), with the downy undercoat shed in the spring – often harvested as cashmere or CFF. Angora goats do not moult.

Moulting presented a significant problem for the evolving permanent ectoparasites (e.g. mange mites and lice) owing to the dramatic changes to their microclimate over the summer period. Consequently, permanent ectoparasites have adapted to seasonal moulting in the host by developing a distinct seasonality of their own. Ectoparasite populations decline in the spring, maintain low populations during the summer and increase again in the autumn, with maximum numbers seen during the winter. Similar seasonality can still be seen in permanent ectoparasites infesting domestic sheep and goats, despite a lack of significant moulting seen in their hosts. This seasonality also ensures that ectoparasites reach optimal numbers in late winter/early spring, in time for horizontal transmission to the spring-born offspring of the host. The stresses and/or physiology of pregnancy may also assist in the generation of optimal numbers of ectoparasites, timed to infest their naive young hosts.

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2

Mites (Acari)

Mites and ticks belong to the Acari, a subclass of the Class Arachnida. The majority of classifications divide mites and ticks (acarines) into three superorders and seven orders. Five of these orders, the Astigmata, Prostigmata, Mesostigmata, Metastigmata (or Ixodida) and Cryptostigmata, contain species that are ectoparasitic on small ruminants (Baker, 1999). These five orders are classified according to the presence and position of the stigmata – the external openings of the respiratory system (Fig. 2.1).

All the major mange mite species are contained within the orders Astigmata and Prostigmata. The Astigmata are a well-defined group of slow-moving, weakly sclerotized mites that include the two families Sarcoptidae and Psoroptidae, which have medical and veterinary importance. The Prostigmata include the Trombiculidae (harvest mites), which are parasitic as larvae but are free-living predators in the nymphal and adult stages, and the true mange mite families Psorergatidae (*Psorobia* (*Psoreregates*) spp.), Demodicidae (*Demodex* spp.) and Cheyletiellidae (*Cheyletiella* sp.). The Cheyletiellidae, being parasites of companion animals, are of no direct significance to livestock production.

The Order Mesostigmata includes the ear mite of goats (*Raillietia caprae*). The Order Metastigmata/Ixodida contains the soft and hard ticks, which are described in detail in Chapter 3. Some genera of mites in the Cryptostigmata contain species that are intermediate hosts of parasitic cestodes (e.g. *Monezia* spp.) of sheep and goats.

Basic Mite Biology

Mite life cycles

An overview of the typical acarine life cycle is described by Baker (1999), as follows. The majority of acarines associated with small ruminants are oviparous, laying eggs in which the embryos are at an early stage of development. Up to four active stages (instars) occur between egg and adult; these include the six-legged larva and two eight-legged nymphs (protonymph and tritonymph). The basic acarine life cycle has been variously modified. For example, the tritonymph does not occur in the Mesostigmata (e.g. *Raillietia* spp.), and there is only one nymphal stage in hard ticks, while the soft tick genera *Argas* and *Ornithodoros* have several nymphs, depending on the quality and amount of the previous blood meal. Moulting takes place between each instar, lasting 12–36 h for the sheep scab mite (*Psoroptes ovis*).

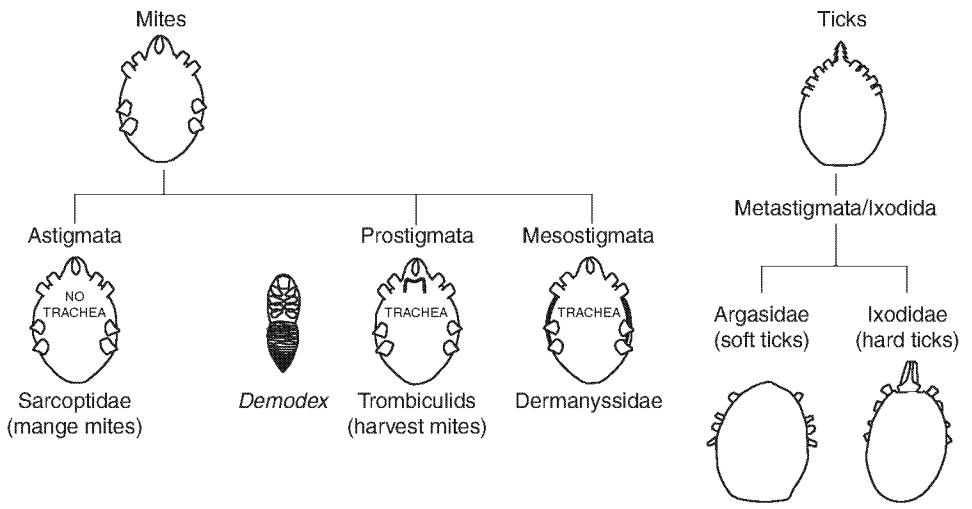

Fig. 2.1. Classification of the Acari (a subclass of the Class Arachnida), which are subdivided into the Astigmata, Prostigmata and Mesostigmata (according the relative position of the peritreme and stigmata), and the ticks (Metastigmata/Ixodida), which are subdivided into the soft ticks (Argasidae) and hard ticks (Ixodidae) according the relative position of the capitulum.

Marked morphological differences between sexes can occur in those groups where the male transfers sperm directly to the female (which occurs in ticks and most mites associated with small ruminants). In these cases, the male is usually smaller and may have a differently shaped body to the female, a different complement of sclerotized shields, a pair of suckers flanking the anus, modified cheliceral digits, and suckers and spurs on certain legs. Immature instars (larvae and nymphs) generally resemble their respective adults, except that they are less sclerotized and lack certain setae and genitalia. Exceptions are the ectoparasitic larvae of harvest mites (Trombiculidae), which look quite different from the free-living nymphs and adults and the hypopus (pl. hypopi) of the Tyroglyphidae. Hypopi occur between the protonymph and tritonymph stages in free-living forage mites, and are produced when environmental conditions are unfavourable; they are non-feeding and immobile resistant forms in which the mouthparts are absent or reduced (Baker, 1999).

Mite morphology

The general acarine body plan has been reviewed by Baker (1999) and is shown in Fig. 2.2. The main part of the body (the idiosoma) is typically sac like, with the mouthparts (gnathosoma = capitulum) forming a discrete structure at the anterior (forward) end, either slightly ventrally (in most mites and soft ticks) or terminally (in a few mite families and hard ticks). The four pairs of legs are inserted ventrally along approximately the anterior half of the idiosoma (the propodosoma) and, from anterior to posterior, are annotated as I, II, III and IV (larvae lack leg pair IV). The part of the idiosoma behind the legs is called the opisthosoma, its dorsal and ventral surfaces being, respectively, the opisthonotum and the opisthogaster. The posterior half of the idiosoma is known as the hysterosoma.

The leg of a typical mite is seven jointed, giving the coxa, trochanter, femur, genu, tibia, tarsus and pretarsus (pedicel, pulvillus, ambulacral stalk). The pedicel bears an 'ambulacrum' composed of a pair

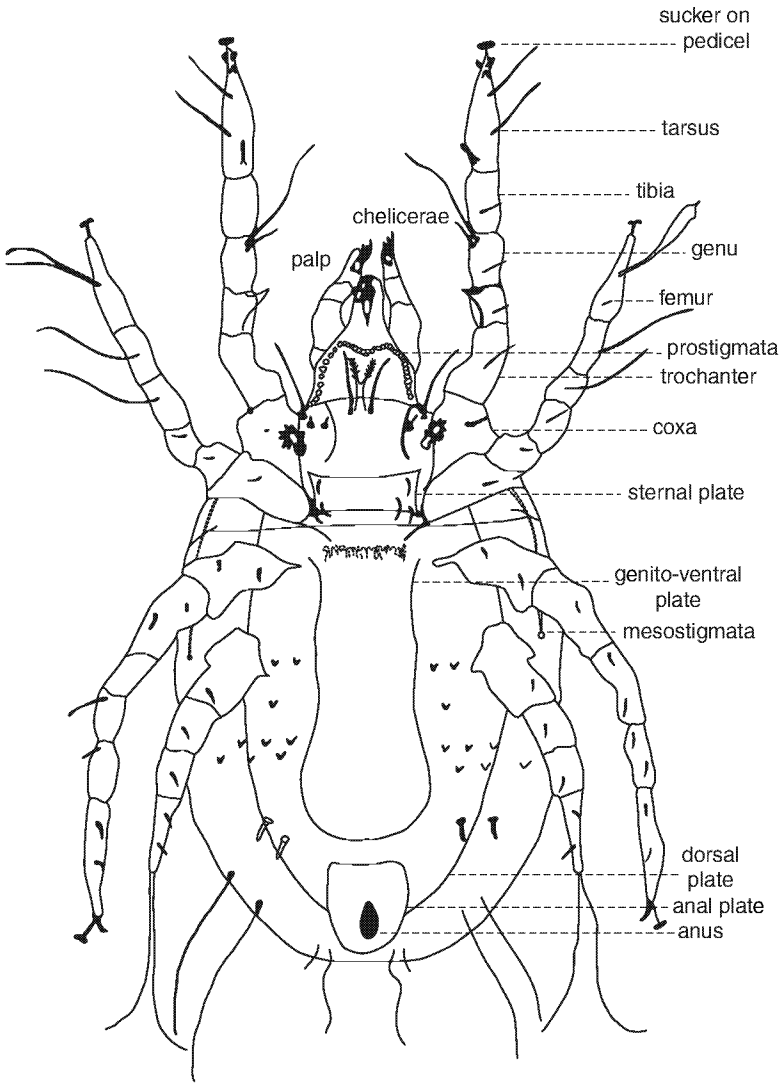

Fig. 2.2. Generalized morphology of a typical mite, highlighting structures used in identification.

of claws, a median empodium and possibly a terminal membraneous pulvillus. The empodium may be hairlike, pad-like or sucker-like. Most mange mites are globose or oval in outline, with the exception of the 'worm-like' *Demodex* sp.

In the larger mesostigmatid mites gaseous exchange is facilitated by a complex tracheal system, which opens to the exterior at the stigmata. In mesostigmatid mites there is one pair of stigmata laterally located; in the prostigmatid mites the stigmata are located behind the mouthparts. Stigmata are absent in the Astigmata, with gaseous exchange occurring directly through the moist cuticle.

As the chitinous exoskeleton hardens with age, it gradually turns brown (sclerotization). Localized areas of heavier sclerotization (shields or plates) occur on the idiosoma; in weakly sclerotized mites, these shields can sometimes only be detected because they

lack the striations of the surrounding area (Baker, 1999). Hair-like extensions of the cuticle (setae) occur on the gnathosoma, idiosoma and legs; different types of setae are sensitive to touch, vibrations or chemicals. The number, arrangement and shape of the shields and setae are used to distinguish between different groups of acari and between different instars (Baker, 1999).

Identification

Detailed keys for the identification of parasitic mites to species level are given in a number of specialist textbooks, including that of Baker (1999).

Acarines as disease agents

Mange (scabies) is a form of allergic dermatitis characterized by encrustation, alopecia and pruritus of the skin. It is initiated by and maintained by a number of mite species contained within the Orders Astigmata (*Chorioptes*, *Psoroptes* and *Sarcoptes*) and Prostigmata (*Demodex* and *Psorobia*). The Prostigmata also include the Trombiculidae (harvest mites), which are semi-permanent ectoparasites that are blood feeding as larvae but free-living predators in the nymphal and adult stages. All members of the Metastigmata/Ixodida (ticks, see Chapter 3) are also semi-permanent ectoparasites that feed on the blood of small ruminants. The blood-feeding habits of the Metastigmata/Ixodida render them important vectors of disease in small ruminants. Astigmatic *Psoroptes* spp. mites inhabiting the ears of goats have been shown capable of carrying mycoplasma infections (possibly pathogenic) between goats (Cottew and Yeats, 1982; DaMassa, 1990).

Astigmatid Mites

Ectoparasitic members of the Astigmata causing mange in small ruminants include the genera *Psoroptes*, *Chorioptes*, *Sarcoptes* and genera within the free-living (tyroglyphid) forage mites (which cause transient mange).

Psoroptes (Psoroptidae)

Mites within the genus *Psoroptes* are cosmopolitan, obligate ectoparasites parasitizing the ears and bodies of herbivores (Fig. 2.3). *Psoroptes* spp. mites are characterized by strongly developed legs bearing, in all stages, funnel-shaped suckers (pulvilli) on long, three segmented pretarsi (peduncles) (Fig. 2.4).

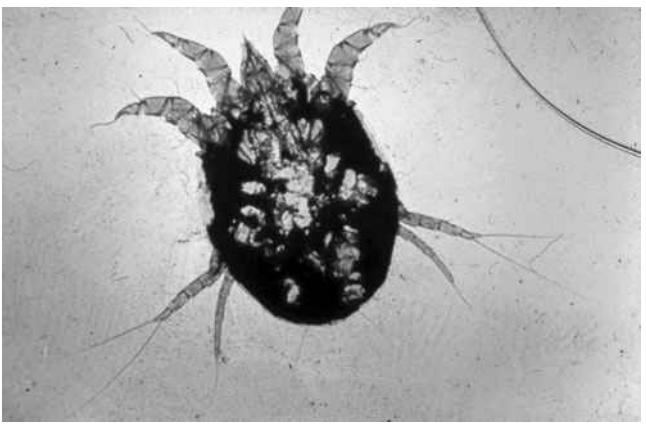

Fig. 2.3. Light microscope image of an adult female *Psoroptes ovis*, the sheep scab mite (Photo © Crown Copyright 2011).

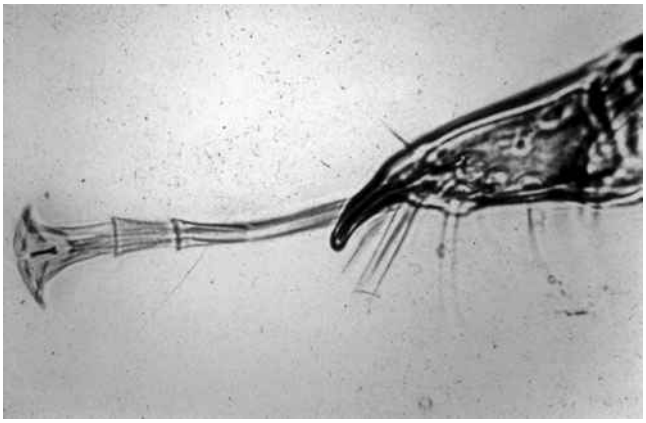

Fig. 2.4. The characteristic terminal, funnel-shaped sucker (pulvillus) of *Psoroptes* spp. on a long, three-segmented pretarsus (peduncle) (Photo © Crown Copyright 2000).

Two species of *Psoroptes* spp. have been recorded to infest sheep: *Psoroptes cuniculi* which infests the ears, and *P. ovis* which infests the body (Sweatman, 1958). In Britain, *P. cuniculi* has been recorded within tubes of scab situated within the last centimetre of the external auditory canal (EAC), next to the tympanic membrane, from sheep with no recent history of external psoroptic mange (sheep scab) (Bates, 1996a,b). *P. cuniculi* ear mites are morphologically identical to the sheep scab mite (*P. ovis*), but do not initiate clinical scab on transfer to the backs of scab-naive sheep.

Bates (1999a) reviewed the genus *Psoroptes* and concluded that there were only two true species and that these are differentiated by the relative lengths of the male L_4 outer opisthosomal setae (L_4OOS) (Fig. 2.5): *Psoroptes natalensis* (Hirst, 1922) and possibly *P. equi*, in which the length of L_4OOS ranges from 250 to 350 µm; and all other species (including *P. cuniculi, Psoroptes bovis, Psoroptes caprae, Psoroptes hippotis* and *Psoroptes cervinus*), which are regarded as variants of a single as yet unnamed species with a length of L_4OOS ranging from 64 to 258 µm. Throughout this book, however, with respect to earlier literature, body mites will continue to be referred to as *Psoroptes ovis* and ear mites as *Psoroptes cuniculi*.

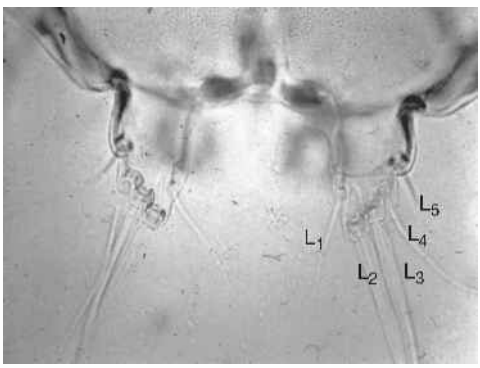

Fig. 2.5. Opisthosomal lobes of male *Psoroptes* spp., showing location of the L_4 outer opisthosomal setae (L_4OOS) which are used to differentiate species of *Psoroptes* (Photo © P. Bates).

Psoroptes *life cycle*

The entire life cycle of *Psoroptes* takes place on the skin of the host and takes 14 days (egg to adult) under ideal conditions.

The sheep scab mite (*Psoroptes ovis*)

Sheep scab mites (*P. ovis*) are non-burrowing, cosmopolitan, obligate ectoparasites that cause a debilitating dermatitis which involves hair or wool loss and a pruritic scab formation. Adult female *Psoroptes* are just visible to the naked eye, at approximately

750μm in length. When colonizing the ear canals of sheep and goats and the bodies of sheep these mites are pearly white and globular in appearance. However, they may appear black to dark red when colonizing the bodies or ears of other hosts (cattle or rabbits), owing to the ingestion of red blood cells (Wright and Deloach, 1980, 1981).

World distribution

In 1986, scab was reported in at least 149 countries throughout the world, with the disease still notifiable in many (Kirkwood, 1986), though many countries (including the UK) have now deregulated sheep scab as a notifiable disease. Although eradicated from Australia, New Zealand and the USA, scab is considered to be a serious threat to the sheep industries of Europe, South America and Southern Africa. Some Member States of the European Union (EU) have organized government-implemented control or eradication schemes; other Member States treat the disease as it occurs, having no national policy. There is a possibility, therefore, that new strains of *P. ovis* (with differing susceptibilities to ectoparasiticides) can be 'imported/exported' throughout EU Member States, particularly in light of the Single European Market.

Seasonality

Sheep scab is a winter disease (Fig. 2.6), with the majority of cases occurring between September and April in the northern hemisphere, although a significant number of cases do occur in the summer months, particularly on animals that are still full fleeced (lambs, shearlings, etc.) and on 'ridges' of longer fleece on poorly shorn sheep (Bates, 1991a). These subclinically infested sheep can later infest ewes with an adequate fleece length. Shearing can stop the progress of disease (either temporarily or permanently) by removing the microclimate, which leaves the mites exposed to dehydration.

The traditional theory for scab seasonality was that mites infesting sheep with short wool were exposed to sunlight, low humidity and extremes of heat, and thus were very slow to colonize and exhibited a very long subclinical phase, with rapid growth only occurring when the fleece length was long enough to matt together and form a suitable microclimate (usually in the autumn). Observations on seasonal artificial infestations of sheep with *P. ovis* have shown that it is increasingly difficult for mites to establish on sheep that are still full fleeced in May, June or July. However, once shorn, *P. ovis* readily established on sheep

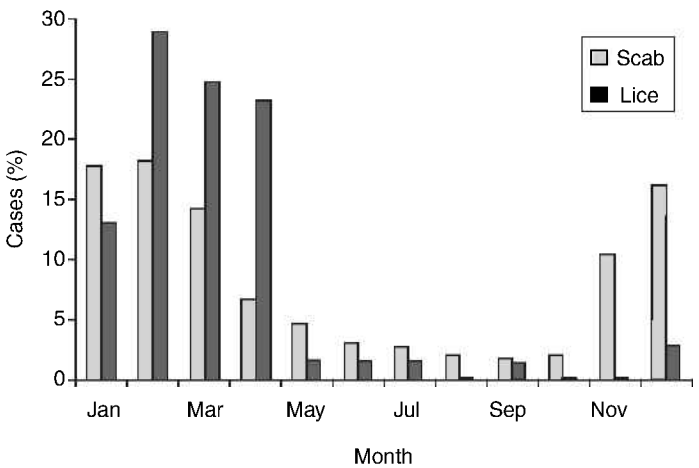

Fig. 2.6. Graphical representation of the seasonality of the sheep scab mite (*Psoroptes ovis*) and of sheep chewing lice (*Bovicola ovis*) in Great Britain, 1997–2004.

with 1.0 cm of fleece. Thus, excessive wool grease ('yolk') may inhibit *P. ovis* colonization during the summer.

Latent phase

Populations of *P. ovis* were once thought to diminish (often to extinction) or actively to migrate to 'cryptic' or 'latent sites' (i.e. the face or tear glands in front of the eyes (the infra-orbital fossae, or IOF), the foot or scent 'glands' between the hooves (interdigital fossae, or IDF), the ears, the inguinal pouches, the crutch and the perineum) at the onset of summer, remaining quiescent until the onset of autumn/winter. This phenomenon of 'latent phase' or 'suppressed' scab was first described by Downing (1936), and later expanded upon by Spence (1949) who showed that mites will enter the cryptic sites 45–60 days after the onset of the active phase of the disease. The migration of *P. ovis* to the cryptic sites is not in dispute, but the intentional seasonality of this migration is open to question. The cryptic sites are only infested on sheep with extensive disease, and then more often in the winter than the summer (Kirkwood, 1985). Roberts and Meleney (1971) recorded only 7% of sheep with detectable infestations in one or more cryptic sites during the summer compared with mites over-summering on the broad body surfaces of 32% of sheep examined.

Transmission and survivability off the host

The transmission of scab mites (and other mange mites) can be either: (i) direct, through sheep-to-sheep contact; or (ii) indirect, through contact with residual mites in the environment.

DIRECT TRANSMISSION. Direct transmission is through sheep-to-sheep contact at mating, at market, in livestock lorries, etc. Sheep with subclinical scab look perfectly normal and can easily be introduced to a flock via market purchases.

If one sheep with subclinical scab is introduced to a scab-free flock via these sources it will not pass mites on to other sheep or the environment while the infestation is still subclinical. The lesion has to enter the rapid-growth phase, in which the mite population is large enough to pass to naive sheep and the pruritic effects of the lesion cause sheep to behave in a manner effective in depositing mites in the environment. Thus, scab is generally well embedded in a flock at the point of veterinary involvement (Bates, 2009a). Results of a study investigating the epidemiology of scab within ten naturally infested sheep flocks in England and Wales showed that from 8% to 60% of sheep can be infested at the point of veterinary intervention, with lesion areas ranging from 1.0 cm^2 to extensive body cover (Bates, 2009a). The study also highlighted that most lesions (54.8%) were located in an area from the neck to the mid-back and extending above the right and left forelegs (with the majority over the withers and mid-back) (Bates, 2009a).

INDIRECT TRANSMISSION. Indirect transmission is through residual mites in the environment – on tags of wool or scab attached to brambles, fencing, farm machinery, animal housing, etc.

Although *Psoroptes* spp. mites are obligate parasites, they are still capable of surviving off the host for significant periods of time. Studies by Liebisch *et al.* (1985) demonstrated that *P. ovis* could survive off the sheep for 48 days and suggested that infested housing must be kept free from sheep for at least 7 weeks. However, once off the host, mites will become malnourished and dehydrated if they cannot find a new host (Wilson *et al.*, 1977). Consequently, *P. ovis* can survive off the host for long periods of time, but will only remain infestive to a new host, given the correct environment, though the mites will only be infestive to sheep for 15–16 days (O'Brien *et al.*, 1994a). In a field situation, predation by other arthropods may also be significant. An optimal microclimate is essential for survival. The maximum survival of *P. ovis* and *P. cuniculi* at 95% humidity decreases linearly with increasing temperature – from 15 days at 9°C to 5 days at 30°C (Smith *et al.*, 1999). Maximum survival off the host is therefore longer at low temperatures and high humidity (i.e. winter).

An infestation can be initiated by only one egg-laying female or hundreds of mites, depending both on the mite burdens on other infested sheep or in the environment, and on the relative period of contact. Infestations can spread rapidly through lowland flocks with restricted grazing, but may be slower through hill flocks which are thinly spread over common grazing and infrequently mustered (Spence, 1951).

Data have shown that outbreaks of scab in Britain originated from lateral spread from contiguous flocks, strays, etc. (33.9%), from movement of sheep via market (22.3%), from direct sheep movements (15.9%) and from persistent infestations on unenclosed land (1.0%) (Table 2.1) (Bates, 2000a). Although this direct transmission was the predominant method, an element of indirect transmission is present in all outbreaks, i.e. via mites deposited at marts, in livestock lorries, etc. Although the origins of the outbreaks were fully explained in over 73% of cases, the origins of infestation remained obscure in 18.5% of flocks and disease recrudesced in 0.7% of flocks (Bates, 2000a). Long periods of latency and a sudden increase in the vigour and pathogenicity of a mite strain could account for unexplained outbreaks of disease (Roberts and Meleney, 1971).

Table 2.1. Breakdown of the origins of sheep scab (*Psoroptes ovis*) in Great Britain from 1983 to 1988 (Source: Bates, 2000a).

Origin of infestation	No. of cases	Percentage
Lateral spread (from contiguous flocks, strays, etc.)	132	34.0
Movement of sheep via market	87	22.4
Obscure	72	18.5
Direct sheep movements	62	15.9
Under investigation (May 1988)	28	7.2
Persistent infestations on unenclosed land	4	1.0
Recrudescence	3	0.7
Total	388	100.0

Feeding

Sheep scab mites (*P. ovis*) infesting cattle and laboratory rabbits are known to ingest blood serum and erythrocytes (Wright and Deloach, 1980, 1981), but this has not been observed in *P. ovis* infesting sheep. Ingestion of whole blood is not specific to a particular *Psoroptes* spp., but may be related to the thinness of the skin in the rabbit's ear and to the larger number of peripheral blood vessels, allowing blood to be ingested more readily. Sheep skin may be thicker and more difficult to penetrate, together with fewer and deeper capillaries, so reducing the opportunity for the mites to penetrate and ingest erythrocytes (Wright and DeLoach, 1981).

Scanning electron microscope studies of *P. cuniculi* and *P. ovis* have revealed an arrangement of chelicerae with a pre-oral trough and a pharyngeal lumen similar to that of solid feeding mites (e.g. *Acarus siro*), as well as a sponge-like 'lapping' organ (the pseudorutella) (Rafferty and Gray, 1987) (Fig. 2.7).

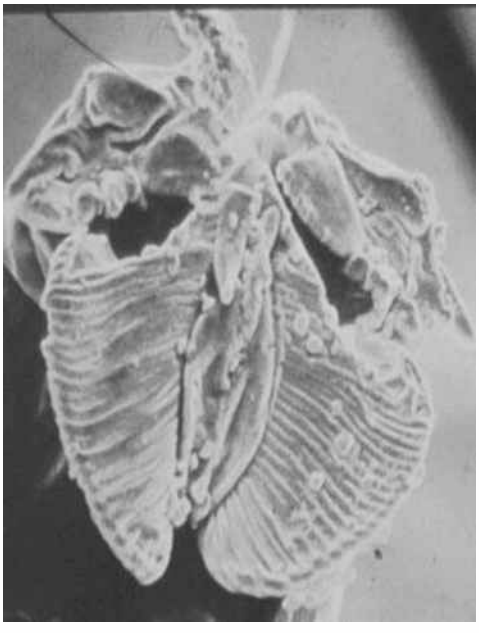

Fig. 2.7. Scanning electron microscope image of the mouthparts of *Psoroptes ovis* isolated from a calf, showing the chelicerae and the sponge-like 'lapping' organ (the pseudorutella) (Photo © Crown Copyright 2000).

Mites can cut, tear and abrade the host epidermis with the toothed, chelate chelicerae, causing the flow of serous exudate (Blake *et al.*, 1978). The pseudorutella may also help to abrade the skin and channel fluid via the preoral trough to the pharynx (Rafferty and Gray, 1987). Salivary glands and associated ducts have not been observed in a detailed study of the mouthparts of *P. ovis*, and salivary secretions are not therefore involved in the formation of the feeding lesion. *Psoroptes* spp. mouthparts are adapted for both solid feeding and for pool feeders (telmophages) feeding on liquid lysed tissue (Rafferty and Gray, 1987).

Histological examination of 'snap frozen' scab biopsies suggest that *P. ovis* on sheep feeds exclusively on skin lipid (Sinclair and Kirkwood, 1983), but limited enzyme assays of mite extracts showed no significant lipase activity (Bates, unpublished data). Lipid is therefore probably not a significant part of the mite's diet; it may be ingested but not necessarily digested. Mites graze the skin around the moist periphery of the lesion, taking in nutrients with the serous exudate, skin secretions and lipid (Bates, 1991b). Mathieson (1995) confirmed experimentally that *P. ovis* ingests serum components likely to be present in the surface exudate that is associated with clinical sheep scab.

Ovigerous (egg laying) *P. ovis* females readily feed throughout their adult life at least in an *in vitro* system. This is contrary to early suggestions that they only fed minimally, if at all, after a single engorgement following their final moult to adulthood (Mathieson, 1994).

Pathogenicity

Although *P. ovis* possesses mouthparts capable of piercing and scraping the skin, and fused palps forming a sponge-like 'lapping' organ, the pseudorutella (Rafferty and Gray, 1987), the clinical signs of sheep scab are caused only partly, if at all, by the direct action of mite feeding. Scab is a form of allergic dermatitis, initiated by allergens contained in the mite faecal pellets. *P. ovis* exploits this allergic reaction; the heat and humidity produced by the inflammation form the microclimate needed for mite survival, and the leakage of serous exudates forms the basis of the mites' nutrition. In this inflamed condition, skin breakages occur, mainly as a result of host scratching but also through small haemorrhages caused by the abrasive action of the mite mouthparts. These skin breakages result in the leakage of serum, with accompanying scab formation and skin thickening (Rafferty and Gray, 1987).

As in all acarines, the chief nitrogenous catabolite of *P. ovis* is the highly insoluble purine, guanine. Excreta are voided in the form of a distinct, dry, solid faecal pellet, surrounded by the peritrophic membrane (PM). The acarine PM remains intact in air but readily breaks down in water (Evans, 1992). In Astigmata, the PM is considered to be secreted by cells of the mid-gut wall (Mathieson, 1995). The arthropod PM typically consist of a meshwork of chitin containing microfibres embedded in a matrix, the principle constituents of which are proteins, glycoproteins and mucopolysaccharides (Spence, 1991; Peters, 1992). The entire digestive system of *P. ovis* contains a significant population of luminal bacteria and these can be found in large numbers in the faecal pellets (Mathieson, 1995); breakdown products from these bacteria may also be allergenic. Furthermore, it has been known for some time that bacteria may play an integral role in the biology of certain arthropods, e.g. the intracellular *Wolbachia pipientis* enhances its own vertical (inherited) spread into an arthropod population by manipulating the reproductive biology of its host (O'Neill, 1995).

Investigations into the diversity of the bacterial flora of sheep skin have been carried out by Merrit and Watts (1978), Meritt (1981), Jansen and Hayes (1987), Lyness *et al.* (1994) and Bates (2003). Bacterial species isolated from scab (*P. ovis*)-naive sheep fleece/skin were (in order of frequency): *Enterobacter cloacae*, *Bacillus* spp., *Bacillus pumilus*, *Staphylococcus epidermidis* and *Bacillus cereus*, all Gram-positive with the exception of *E. cloacae* (Bates, 2003). Following infestation with *P. ovis*, the bacterial species on the same sheep change to

include (in order of frequency): *Serratia marcescens*, *S. epidermidis*, *Corynebacterium* spp. and *Escherichia coli*. *S. marcescens* was also isolated in large numbers from the crushed *P. ovis* infesting the sheep (Bates, 2003). Mathieson and Lehane (1996) postulated that *S. marcescens* was associated with *P. ovis*, and studies in Italy by Perruci *et al.* (2000) have shown that the ear canker mite of rabbits (*P. cuniculi*) also carried an internal bacterial flora and that *Serratia* spp. were present. In addition, Hogg and Lehane (1999) identified a possible association between *Alloiococcus otitidis* and *P. ovis*. *S. marcescens* may be essential to and carried by *P. ovis*. However, *S. marcescens* was never isolated from field isolates of *P. ovis*, and the bacterial flora varies with the *Psoroptes* isolate (Bates, 2003). *S. marcescens* may be airborne contaminants in hay dust, etc., and only be ingested by mites once they are proliferating in the changed microclimate on the infested sheep (Bates, 2003).

P. cuniculi may have an important role in the spread of pathogenic *Mycoplasma* spp., transmitting the organism between the ears of goats (DaMassa and Brooks, 1991). Perruci *et al.* (2001) demonstrated that when bacteria had been removed by antibiotic treatment, *P. cuniculi* was still capable of causing clinical disease in rabbits, and deduced that the mites do not need the intestinal bacteria to live or to cause pathogenesis, and they may actually inhibit the development of infestation. The possible inhibitory effect of bacteria must not be underestimated. It must not be forgotten that the three macrocyclic lactone acaricides (doramectin, ivermectin and moxidectin) are derived from species of *Streptomyces*. Organisms in the *B. cereus* group (including *Bacillus thuringiensis*) form a series of characteristic protein inclusions adjacent to the endospore (insecticidal crystal proteins, or ICPs) that are toxic to certain species of arthropod. Similar ICPs are also thought to be produced by *S. marcesens* (WHO, 1999). Investigations into the entomotoxicity of the bacterial flora of sheep skin may highlight potential control strategies against sheep scab and other ectoparasites.

Skin bacteria may have more profound effects on the biology of *Psoroptes* mites. They may be responsible for variations in susceptibility between individual sheep. Mites have to adapt to differences in skin flora between hosts; those that cannot adapt to the new flora are unable to initiate infestations. Similarly, bacterial flora may be significant in regard to host specificity; the bacterial flora on a sheep may be different to that on goats and thus inhibitory to mite colonization. Bacterial flora may play an important role in differences in the relative virulence of *P. ovis* (Bates, 2003).

Disease progression

In many host–parasite relationships there is a period of parasite increase, followed by stability, then by decline (Matthyse *et al.*, 1974). Six such phases have been observed in the temporal progression of sheep scab (Figs 2.8 and 2.9), as populations of *P. ovis* adapt to the changing ecological conditions confronting them (Bates, 1997a):

1. The subclinical (colonization, lag, prepatent or sensitization) phase.
2. The rapid growth phase.
3. The peak (plateau, maturity, climax) phase.
4. The decline (death or decay) phase.
5. The regressive phase.
6. The cryptic phase.

These phases can be deduced by recording the temporal changes in: (i) the numbers of live adult female *P. ovis in situ* around the periphery of the lesion; (ii) the area of the scab lesion itself; and (iii) the anti-*P. ovis* IgG titre, deduced by ELISA (Bates, 1997a).

THE SUBCLINICAL PHASE. The subclinical phase is characterized by low mite numbers and small lesions (below 2.5% of body cover). Initial observations of lesions in this phase are similar to those recorded by Downing (1936) and Spence (1949), with mites feeding within hours of contact; after feeding for a minute, an inflamed small vesicle, filled with clear lymph develops, surrounded by a zone of inflamed skin. This is followed by vesication, rupture and exudation of serum.

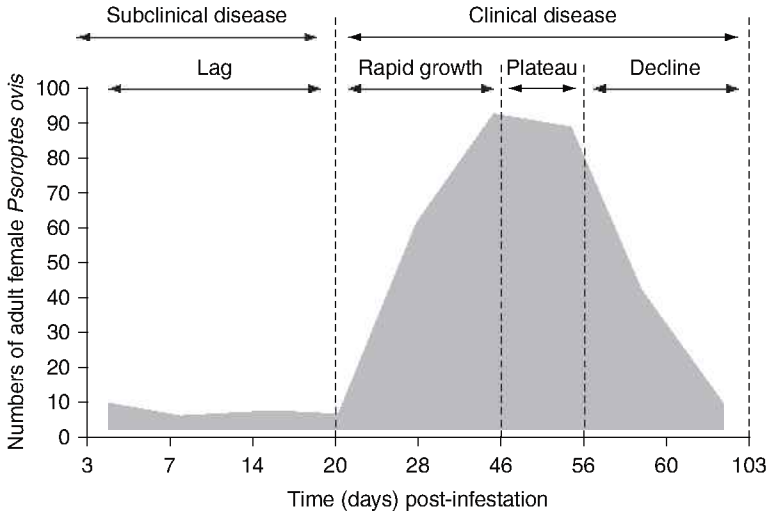

Fig. 2.8. Graphical representation of the progress of sheep scab (psoroptic mange) showing increase in mite numbers with time under laboratory conditions.

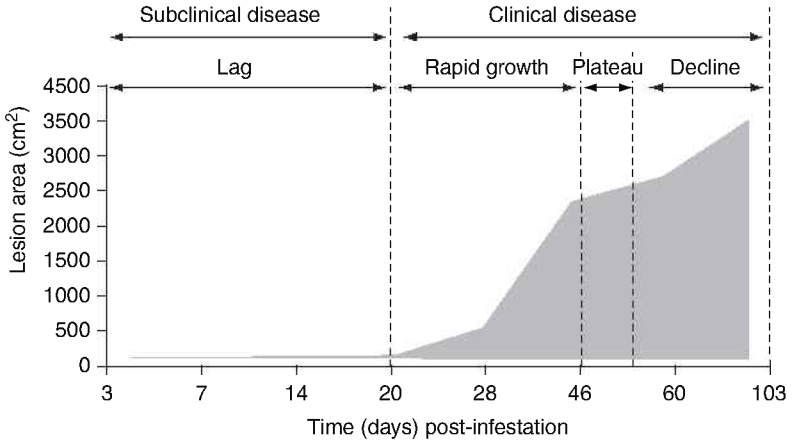

Fig. 2.9. Graphical representation of the progress of sheep scab (psoroptic mange) showing increase in lesion area with time under laboratory conditions.

Generally, these vesicles develop into pustules, which increase in size before rupture and discharge. Infection of the pustules by pyogenic bacteria causes them to have a greenish yellow colour. Later, crusts are formed by the disintegration of the cuticular layers of the skin, and the accumulation of serum and purulent matter derived from the ruptured vesicles and pustules. One of the obvious characteristics of the subclinical phase is that these lesions are virtually undetectable unless the sheep is examined thoroughly (Bates, 2009a). Pruett *et al.* (1986) postulated that the resulting seepage of serous fluid could enhance the feeding environment of the mite. Following challenge with *P. ovis*, there is a rapid (within 24 h) inflammatory influx of eosinophils and apoptosis of the keratinocytes at the site of infection (Huntley *et al.*, 2005).

As implied above, one of the obvious characteristics of the subclinical phase is that infested sheep are virtually undetectable. In laboratory infestations, using 25 (medium virulent) adult female *P. ovis* from the VLA (Veterinary Laboratories Agency) Reference Isolate, no obvious clinical signs of infestation were observed until 48 days post-challenge, when a noticeable discoloration of the wool was observed over the site of challenge. A humoral immune response is elicited against *P. ovis*, but circulating antibodies are not detected until the lesion itself covers 1.27% of the body and the infestation enters the rapid growth phase (Bates, unpublished observations). Vishnyakov (1993) demonstrated that there was also a change in the immune status at the T-lymphocyte subpopulation level within 30–40 days after artificial infestation.

In laboratory studies, the subclinical phase can last for 14–40 days, during which period the mite adjusts to the new host and the host responds immunologically to the mite. If the sheep is unable to mount the correct allergic response, the appropriate microclimate and feeding environment are not initiated and the mites cannot colonize. Conversely, if the sheep is immunologically responsive (susceptible), an active lesion is produced. These clinical observations support those of Stockman (1910), who showed that experimental infestations remain undetectable until from 25 to 30 days post-challenge, even with a challenge higher than expected in the field; however, the time period from contact to presentation of clinical signs in the field can be over 240 days. Progression to the rapid growth phase may be slow on sheep of low scab susceptibility, but considerably shorter on sheep that are susceptible to infestation. Roberts and Meleney (1971) recorded that infestations could escape detection for over a year. Long periods of latency and a sudden increase in the vigour and pathogenicity of a mite strain could account for unexplained outbreaks of the disease.

THE RAPID GROWTH PHASE. Following the subclinical phase, the disease may then enter the 'rapid growth phase', which is characterized by a rapid increase in mite numbers, lesion spread, an increase in circulating IgG and a definite increase in clinical signs of infestation. Body heat will dry the serous exudate to form the scab. *P. ovis* (being semi-liquid pool feeders) cannot feed on the hardened scab and this, together with the hyperkeratinized skin and build-up of toxic faecal material, means that they are forced to aggregate at the periphery of the expanding lesion.

Early disease is confined to the dorsal and lumbar areas but, if the condition remains untreated, it may extend over the whole sheep, down the flanks and limbs, and also on to the head, face and tail (Fig. 2.10). Pathological changes at the advancing margin of the lesion are more severe than at the initial site of infestation, and this is reflected by the numbers of mites present. These data suggest that *P. ovis* may elicit an early innate cutaneous response that is subsequently augmented by the development of an adaptive immune response, the intensity of which corresponds to the local population density of mites (Broek *et al.*, 2004). In the later stages 'flaker' sheep may occur; these are characterized by extensive wool loss, usually on the flanks and withers, with the denuded areas covered in a pavement of flakey ('cornflake') scabs, overlying thousands of active mites (Fig. 2.11).

The lesion gradually spreads outwards as the mite population increases. Rubbing and head tossing become more excessive, areas of wool loss may appear, together with open, bleeding wounds. Sheep rapidly lose condition and epileptiform seizures may be evident (Bygrave *et al.*, 1993). In the later stages mites begin to migrate to the 'cryptic sites' (the pinnae, IOF, inguinal fossae and the perineum) and the external auditory canal (EAC) (Bates, 1997a, 2000a). Spence (1949) observed that colonization of the cryptic sites occurred 45–60 days after the onset of the rapid growth phase. High populations of mites during this phase render it more likely for them to pass to other sheep, either by direct or indirect contact. Antibody titres continue to increase, but eventually the lesion growth

Fig. 2.10. Sheep presenting with clinical signs of sheep scab (psoroptic mange) in the later stages of the active growth phase (Photo © P. Bates).

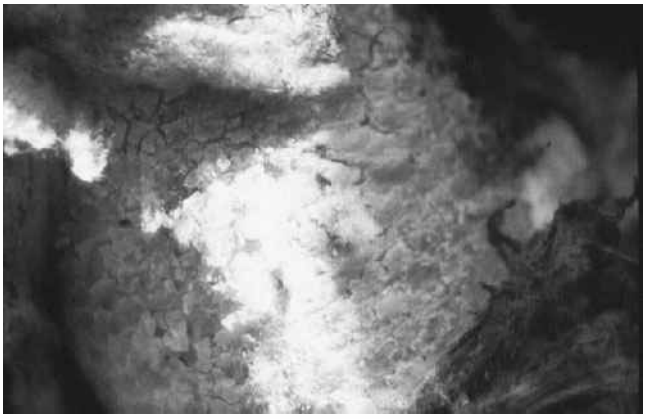

Fig. 2.11. Sheep scab (psoroptic mange) 'flaker' sheep, characterized by extensive wool loss, usually on the flanks and withers, with denuded areas covered in a pavement of flakey ('cornflake') scabs, overlying thousands of active *Psoroptes ovis* mites (Photo © Crown Copyright 1997).

slows down or stops completely and the mite population decreases rapidly as the disease enters the 'decline phase'.

THE DECLINE PHASE. In this phase, the general appearance of the lesion changes; the active moist edge becomes indistinct and scaly. Aural haematoma and secondary bacterial infections may also occur (Bates, 1997a). Mite populations decrease, partly as a result of the lack of feeding sites, but also because of the immune response elicited by the host. Infestations of *P. ovis* result in a profound intradermal inflammatory response with the generation of IgE and IgG antibodies. *P. ovis* antigens have therefore been implicated in the development of the pathology and/or the development of immunity to infection, and may also offer new candidates for novel therapies, including vaccine production (Nisbet *et al.*, 2006). Immunoglobulin has been shown to be

secreted onto the skin in concentrations comparable to circulating levels (Watson *et al.*, 1992), and this may mediate immunological protection. Ingested dermal immunoglobulin may affect mite fecundity and survival by attacking the mid-gut cells of the mite (which also form the PM of *P. ovis*), and by inhibiting nutrient absorption and, ultimately, egg production (Stromberg and Fisher, 1986). The lack of feeding sites and the host immune response may also force the mites to disperse at random over the entire body, with many continuing to reach the cryptic sites (Bates, 1997a). Mite faeces are still bound to the dried scab and will continue to elicit irritation as long as the scab is in contact with the skin.

THE REGRESSIVE PHASE. Eventually, new wool growth begins in previously denuded areas and the scab continues to lift away from the skin as the wool grows; this constitutes the 'regressive phase' (Fig. 2.12).

THE CRYPTIC PHASE. Sheep appear to recover completely from the disease, but they may still be harbouring small populations of mites, under dry scabs or in the cryptic sites, which are waiting to reinfest the sheep once normal skin conditions are restored ('pseudorecovery'). It is not unusual for the mite population to disappear completely and for an animal to make a full natural recovery without acaricidal treatment. In this 'cryptic phase', previously infested sheep may appear clinically normal, but mites can still be found in the EAC or IOF.

Factors that can influence the length of the subclinical phase and the general speed of lesion growth include mite virulence, the age and sex of the sheep, sheep breed, natural resistance, concomitant infestations/infections, previous exposure to *P. ovis*, the challenge dose and the challenge site (Bates, 1997b). These are discussed next.

Mite virulence

Roberts and Meleney (1971) observed that distinct populations of *P. ovis* existed in the USA. The differences between them were based upon: (i) the success of certain isolates to withstand population reduction in the summer; (ii) the survival of these more aggressive isolates in contact with organophosphate acaricides compared with less aggressive isolates; (iii) the longer survival of aggressive isolates on sheep in isolation; and (iv) the ability of aggressive isolates of sheep origin to spread through herds of cattle more rapidly and to present more obvious clinical responses than those of less pathogenic isolates.

Fig. 2.12. Sheep presenting with clinical signs of sheep scab (psoroptic mange) in the regressive phase of the disease (Photo © Crown Copyright 2011).

Bates (1999c, 2000a) compared 15 British field isolates of *P. ovis* with the then 26-year-old VLA (Central Veterinary Laboratory (CVL) Weybridge) Reference Isolate, for their speed of lesion production and rate of mite population increase. All the geographical isolates of *P. ovis* produced a progressive lesion, characteristic of sheep scab, but the extent of the lesion produced over time varied considerably between isolates (Fig. 2.13).

Effects of age and sex

O'Brien (1996) and Bates (2000a) observed no differences in susceptibility between male and female sheep. The existence of patent infestations on young lambs is equivocal. Downing (1936) saw lesions on young lambs 4 and 7 days old, but recent clinical studies have shown lambs under a month old to only present with circumscribed areas of clean tagged wool ('leopard lambs'), but with no definite lesions observed on closer examination (Bates, unpublished observations).

Effects of sheep breed

The breed of the host can have a profound effect on scab establishment and progress. Fourie *et al.* (1997) demonstrated that the progress of sheep scab lesions was almost five times greater in the South African merino than in the local Dorper breed, and suggested that Dorper sheep may play an important role in the spread of disease. Bates *et al.* (2001b) compared three distinct major breeds for their susceptibility to *P. ovis*:

- The Polled Dorset, a hornless strain of the Dorset Horn, a lowland, short-wool breed producing fine densely grown wool, with a mean staple length of 8.1 cm and a total fleece weight of 2.25–3.0 kg (Skinner *et al.*, 1985).
- The Swaledale, a hardy breed of hill sheep, ideally suited to endure exposure on high lying moorland of northern England. The breed is horned in both sexes, with a mean staple length of 10.2 cm and a total fleece weight of 1.5–3.0 kg, mostly of coarse quality destined for carpet yarn (Skinner *et al.*, 1985).
- The North of England Mule, a result of a Bluefaced Leicester ram crossed with a Swaledale (or Scottish Blackface) ewe. The North of England Mule is currently the most popular commercial breed of sheep throughout the UK, accounting for 14.5% of the British

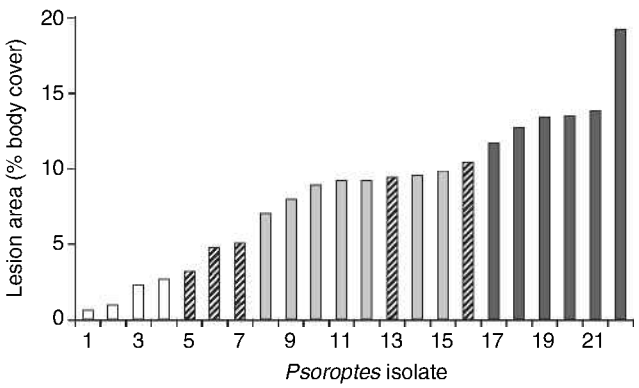

Fig. 2.13. Graphical representation of the relative virulence of geographically distinct populations of the sheep scab mite (*Psoroptes ovis*) in Great Britain shown as lesion area as per cent body cover 28 days after challenge. White bars, low virulence populations; hatched bars, medium virulence populations (Veterinary Laboratories Agency Reference Isolate not significantly different at 5% level, $P = 0.060$); grey bars, medium virulence populations; black bars, high virulence populations (Bates, 1999a, c).

wool clip (used in the manufacture of both knitwear and carpets). It is a horn-less breed, with a mean staple length of 10.25 cm and a total fleece weight of 2.5–3.5 kg (Skinner *et al.*, 1985).

There were great differences in the establishment and progress of scab lesions within these three breeds (Figs 2.14 and 2.15). The Polled Dorsets presented with thick, crusty lesions with well-defined peripheries and a mean per cent body cover of 46.08% after 60 days. The Mules presented similar, if not faster growing lesions (67.12% of body cover) over the same period. One characteristic of infestation on the Mules was that the fleece was matted tightly over the lesion, making it extremely difficult to part. Although a number of Swaledales did present with clinical disease over the 60 days of the study, most were very effective in grooming the challenge area, either by biting or chewing the fleece directly over the challenge site or by scratching it with their horns. This resulted in extensive areas of close-cropped wool over the challenge site, which restricted lesion growth

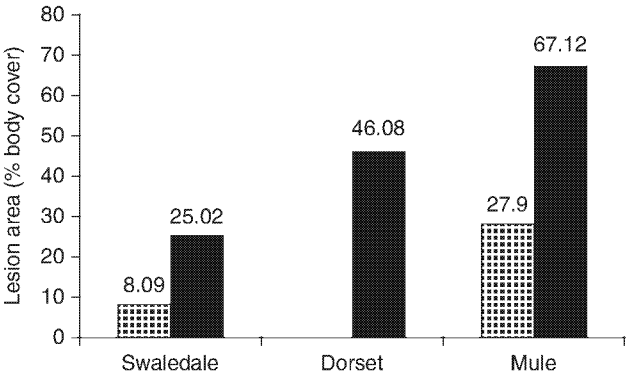

Fig. 2.14. Graphical representation of the progress of sheep scab (psoroptic mange) on three British breeds of sheep under laboratory conditions shown as lesion area as per cent body cover 60 days after challenge (Bates *et al.*, 2001). Black bars, VLA (Veterinary Laboratories Agency) Reference Isolate of *Psoroptes ovis*; hatched bars, field isolate of *P. ovis* from south Wales.

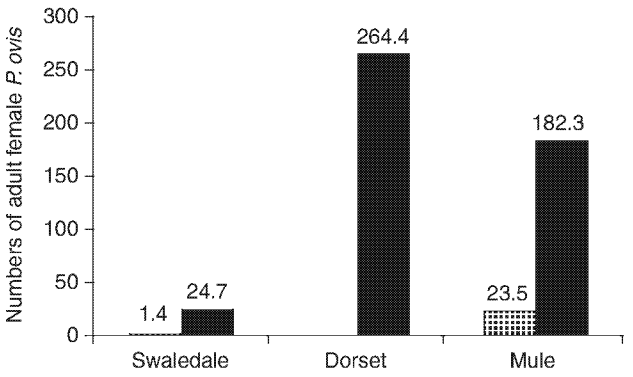

Fig. 2.15. Graphical representation of the progress of sheep scab (psoroptic mange) on three British breeds of sheep under laboratory conditions shown as numbers of adult female *Psoroptes ovis* 60 days after challenge (Bates *et al.*, 2001). Black bars, VLA (Veterinary Laboratories Agency) Reference Isolate of *Psoroptes ovis*; hatched bars, field isolate of *P. ovis* from south Wales.

(to 25.02% of body cover over 60 days) or totally prevented lesion establishment. The mean rate of lesion growth was significantly slower on Swaledales (37 cm^2/day) compared with the Polled Dorsets and the Mules (58 and 84 cm^2/day, respectively). Breed differences were also observed in the numbers of adult female *P. ovis* developing over time. The finer woolled breeds (Polled Dorset and Mule) presented with comparatively high mean mite populations 60 days after challenge (264.4 and 182.3 mites per sheep, respectively). The coarser woolled Swaledales only presented mean populations of 24.7 mites per sheep over the same time period.

Natural resistance to infestation

There is a marked gradation in the severity of disease with time regarding individual sheep challenged with the same number of adult female *P. ovis*, ranging from no lesion formation to extensive scab cover in a matter of weeks. Data obtained from the breed susceptibility study (Bates, 2000a) supported these findings, with individual Swaledale ewes maintaining subclinical infestations (i.e. lesion area below 2.5% of body cover) for well over 60 days, compared with others presenting with 83% lesion cover over the same time period. The length of the subclinical phase depends on the immunocompetence of the individual sheep. If an individual is unable to mount an allergic response to the mite, the lesion will not be permanent, and disease will not progress past the subclinical phase. In contrast, if an individual is immunologically responsive, the infestation will establish and the lesion will enter the rapid growth phase. Rafferty and Gray (1987) showed that the degree of susceptibility of individual rabbits to *P. cuniculi* infestations differed owing to the host's natural resistance to mites. This phenomenon has also been observed on sheep at the VLA (Weybridge), with some animals presenting small lesions with large numbers of mites and others presenting large and expanding lesions with only one or two mites detectable (Bates, unpublished observations).

Concomitant infections/infestations

The chewing louse (*Bovicola ovis*) of sheep is a familiar parasite of sheep on the common grazing uplands of the UK. Sheep with a predisposing infestation of chewing lice will not accept challenges of sheep scab mites, whereas sheep with active scab can easily be colonized by lice following natural exposure (Bates, unpublished observations). The exact nature of this inter-species exclusion is unknown, but the skin changes initiated by louse feeding/excretion may render it unfavourable for mite colonization. Lice, in contrast, may actively feed on the scab lesion (Bates, 1999b). Similarly, any disease or treatment that suppresses the immune system may also affect the progress of infestations.

Ehrlichia phagocytophila is a tick-borne rickettsia that infects ruminants and causes tick-borne fever (TBF). This is associated with fever, abortion and immunosuppression, which in sheep can lead to secondary infections including lamb pyaemia caused by *Staphylococcus aureus*, septicaemia caused by *Pasteurella haemolytica* (*trehalosi*), and infections by parainfluenza-3 virus, louping ill virus and *Chlamydia psittaci* (Brodie *et al.*, 1986). Cell-mediated immune response, as measured by a delayed skin hypersensitivity, is not affected by TBF, suggesting that immunosuppression in TBF is probably due to the effect of *E. phagocytophila* on the cells mediating the humoral immune response (Batungbacal and Scott, 1982). A transient lymphocytopenia has been reported to develop and lambs so affected have been shown to be defective in their abilities to produce antibodies (Batungbacal and Scott, 1982) and to mount cell-mediated responses (Brodie *et al.*, 1986). Larsen *et al.* (1994) demonstrated experimentally that levels of antibody against tetanus toxoid or influenza virus produced by TBF-infected sheep were significantly lower than those in control sheep. TBF infection may impair both primary and secondary responses for up to 6 weeks. Immunosuppression by TBF may also complicate sheep management in areas where TBF is enzootic by interfering with the

response to immunization (e.g. to clostridial vaccines) (Batungbacal and Scott, 1982). The main foci for both sheep scab and TBF are the upland common grazing areas of Britain and, owing to the need for antibody production to control scab infestations, immunosuppression by TBF may have profound effects on the progress of this disease.

Sheep previously exposed to Psoroptes ovis

The phases of scab appear to be significantly altered during reinfestation. Bates (2000b) demonstrated that acquired resistance after a year was manifested by the lesion and mite burden remaining subclinical for over 50 days (Fig. 2.16), thus supporting the observations of Spence (1949). Colonies eventually established and clinical sheep scab was observed, although mite populations remained extremely low. Similar observations have been reported in *Psoroptes* spp. infestations of other hosts (Stromberg *et al.*, 1986; Guillot and Stromberg, 1987; Stromberg and Guillot, 1989; Urlir, 1991). Serum IgE titres are significantly greater in secondary challenge than in primary challenge (Broek *et al.*, 2000). However, this apparent acquired resistance may not be entirely immunologically modulated. Changes in the host skin character and the increased age of sheep also may have influenced the pathology of reinfestation. It has been reported that sheep scab can have a significant effect on the quality of processed leather (Pearson, 1996), suggesting that there are significant changes in the character of the sheep's skin following *Psoroptes* infestation. These skin changes may also make it difficult for mites to feed following reinfestation.

Challenge dose and challenge site

In the field, a sheep may have several challenges with several discrete lesions or, in the later stages, many lesions that are coalescing (Bates, 2009a). Certain areas of the sheep are unfavourable for initial colonization by *P. ovis*, although they will be colonized as lesions spread towards them, as mite populations adapt to the environmental changes presented by the host (Bates, 2000a). Examination of naturally infested sheep in the field has shown that over 51% of lesions occur on the withers and the mid-back (Bates, 2009a). Artificial challenges on the withers, flanks and brisket have resulted in the rapid establishment of mite colonies and extensive lesion growth. However, failure to establish, or slower growth, were recorded on the face, head, tail-head and belly (Bates, unpublished observations). Although it is traditional throughout the UK to dock the tails of sheep in order to prevent fly strike, tails are often left intact in flocks grazing the moors and mountains of Wales. Infestations exclusively confined to these intact tails are

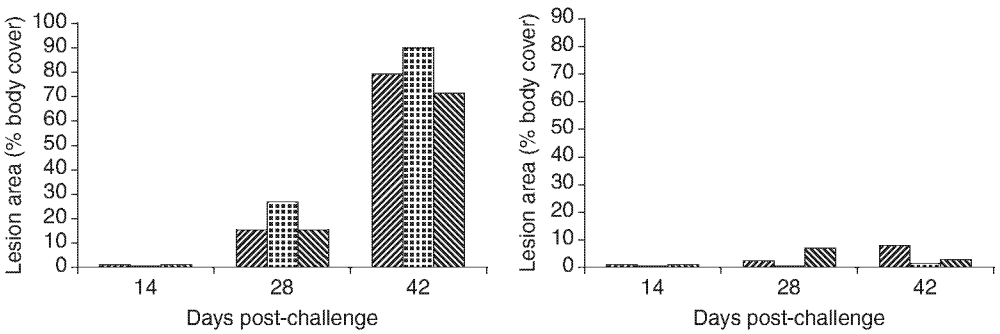

Fig. 2.16. The effects of acquired resistance on the progress of sheep scab (psoroptic mange). The histogram on the left shows lesion growth before resistance was acquired and the histogram on the right lesion growth 1 year post-acquired resistance. The acquired resistance was manifested by the lesion area (and mite burden) remaining subclinical for over 50 days (Bates, 2000b).

not uncommon, with lesions terminating at the tail-head and the remainder of the sheep entirely free of scab lesions. In one Welsh flock investigated, 41 out of 139 (29.5%) of ram lambs presented scab lesions (with active mites) covering the intact tail only, with few or no clinical signs. Temperature may play an important role in the selection of sites suitable for colonization, with the mean temperatures of the cryptic sites, body and tail being 34.2°C, 28.7°C and 20.5°C, respectively (see Table 1.6).

Spread within flocks

Numbers of infested sheep within the flock can vary from one or two animals in the early days of the infestation to the whole flock as the disease takes hold (depending on their immune status of each individual sheep). Throughout the flock, there will be animals with non-established lesions (which will eventually die out) and animals with young subclinical lesions together with animals with obvious extensive disease. All sheep should be considered to be infested and the whole flock should be treated for scab. One missed sheep could reinfect the whole flock.

Clinical signs

Sheep scab is multifactorial in nature and has been described as 'not a disease in the strict sense, but a condition of the skin due to the infestation of *Psoroptes* mites, living and feeding on the sheep'. Scab cases can be completely different to the 'textbook' case: wool loss does not always occur and pruritus varies with each sheep from nil to severe. Gross clinical signs in the later stages of infestation can be excessive. However, some sheep can be extensively covered in a scab lesion and only present with a dense matted fleece.

Scab mites (*P. ovis*) do not travel very far from their initial point of contact and will generally initiate a lesion at this site, if conditions are suitable. Although the majority of sheep (51.1%) will present with a single discrete lesion, it is not uncommon for sheep to present with ten or more individual lesions. During the subclinical phase, these lesions will be discrete, but as the disease moves into the rapid growth phase many of the growing lesions will coalesce to form one large progressing lesion. Lesion areas at the point of veterinary intervention can range from $<10\,cm^2$ to total body cover ($>4000\,cm^2$), in 29% and 4.0% of sheep examined, respectively (Bates, 2009a).

Early subclinical scab is generally asymptomatic. Signs of infestation may include restlessness, rubbing against fence posts, etc., soiled and stained areas of wool (particularly on the shoulders), head tossing and deranged or tagged fleece. However, these could also be the symptoms of other ectoparasite infestations (e.g. chewing lice, *B. ovis*, blowfly strike (caused by *Lucilia* spp.), fly bites, or scrapie), or of a number of non-parasitic skin conditions. In the later stages of infestations, the rubbing and head tossing become more excessive, and areas of wool loss may appear together with open, bleeding wounds. Sheep rapidly lose condition and a touch hypersensitivity reflex may be evident (see next section) (Bygrave *et al.*, 1993).

Touch hypersensitivity response

Scab-infested sheep can manifest an involuntary response – a touch hypersensitivity response (THR), which is scored according to Table 2.2. Affected sheep show a peracute hypersensitivity reaction initiated by handling and/or movement of the flock. The typical nibble reflex can progress rapidly to head tossing, attempted biting and chewing, and involuntary increasingly frenetic scratching of the lesions. Some sheep lose voluntary control, collapse, and show horizontal nystagmus associated with frenzied champing of the jaws and foaming at the mouth. Incoordinated convulsions can develop and last from 10 to 20 min (Bygrave *et al.*, 1993). Forced exercise followed by close penning will increase body heat and the associated percutaneous absorption of mite antigens/irritants, thus inducing the presentation of clinical signs. Blood samples taken during a seizure from two ewes showed normal values for calcium, magnesium and lead, and for cholinesterase activity. There were no

Table 2.2. Sheep scab (psoroptic mange) touch hypersensitivity response (THR) scores.

Score	Behaviour
–	No response.
+	Definite but slight attempts to chew or bite the manipulated lesion and/or lip smacking, but with no direct mouth contact with the body or the lesion itself.
++	As for (+) but with definite mouth contact with the body/lesion and involvement of at least one limb in a scratching response, with symptoms subsiding on removal of the stimulus.
+++	As for (++) but the response is more intense, with symptoms continuing on removal of the stimulus, with the sheep standing at all times.
+++	The sheep falls over in an epileptiform fit.

lesions in carcasses to suggest intercurrent bacterial and viral diseases, and the histology of the brain and spinal cord showed no abnormalities (Bygrave *et al.*, 1993).

If a THR is elicited a lesion is likely to be in the vicinity of the skin palpation. However, field data has shown that over half (54.3%) of scab-infested sheep do not exhibit such a response, thus the THR is not a reliable indicator of infestation (Bates, 2009a). Futhermore, this involuntary response is also a major clinical sign of scrapie.

Psoroptic ear mites

Sheep and goats can be subclinically infested exclusively in the external ear canal (EAC) with *Psoroptes* spp. mites (psoroptic otoacariasis) (Bates, 1992a, 1999a).

Caprine psoroptic otoacariasis

Psoroptes spp. (designated *P. cuniculi* or *P. caprae*) infesting the ears of domestic goats have been reported throughout the world. Most infestations are subclinical, asymptomatic (other than the occasional episode of ear scratching with the hind feet) and are easily overlooked (Schillhorn van Veen and Williams, 1980; Bates, 1992a). *P. cuniculi* has also been isolated from the external ear canals of feral goats in Australia and New Zealand (Heath, 1979; McKenzie *et al.*, 1979; Hein and Cargill, 1981).

The recorded prevalence of caprine psoroptic otoacariasis within herds has been recorded to range from 21% (Cook, 1981) to 87% (Williams and Williams, 1978). Bates (1992a) recorded that 30.0% of English goats examined were affected, with the prevalence within herds ranging from 20.0% to 35.0%, and none presenting with any overt signs of infestation; he estimated that 80.0% of English goat herds could be affected by psoroptic otoacariasis, a figure that is considerably higher than the 22.0% of Australian domestic goat herds recorded as affected by Cook (1981).

Ovine psoroptic otoacariasis

The sheep ear canal can be infested with either *P. ovis* or *P. cuniculi* (Bates, 1999a), and *Psoroptes* spp. mites (designated *P. cuniculi*) have been recorded in the ears of sheep without the clinical signs of body mange (sheep scab). Psoroptic otoacariasis has been recorded in Brazil (Faccini and Costa, 1992), France (Henry, 1917), Germany (Zurn, 1877), India (Shastri and Deshpande, 1983), Israel (Yeruham *et al.*, 1985), South Africa (Van der Merwe, 1949) and Britain (Bates, 1991c; Morgan, 1991, 1992). Henry (1917) found psoroptic otoacariasis in 47.0% of emaciated sheep without clinical sheep scab. Unfortunately, he did not state whether the mites were isolated from the pinnae or from the EAC. Hirst (1922) also described *Psoroptes* spp. in the ears of sheep without their occurrence on the body.

Ovine subclinical psoroptic otoacariasis (*P. cuniculi*) is a common parasite within the British national flock, with 1.4% of lambs shown to be infested (Bates, 1996b). Critical investigations of seven field cases revealed flock prevalences ranging from 1.3% to 23.9%, with the highest infestations

found in pedigree flocks. Commercial ewe flocks, with the exception of flocks where commercial and pedigree ewes were run as joint enterprises, appeared to be relatively uninfested. Only one flock investigated had been directly involved in sheep scab tracing, and in this flock breeding ewes had been purchased by a neighbouring farm and clinical sheep scab confirmed 6 months later (Bates, 1996a).

Historically, the prevalence of ovine otoacariosis in Britain appeared to be increasing, with 0.3%, 1.8% and 3.9% of sheep examined found to be infested in 1989, 1990 and 1991, respectively (Bates, 1996b). The results of a telephone survey carried out by Morgan (1992) revealed 28% of sheep owners reporting ear lesions possibly attributed to psoroptic otoacariasis. With the deregulation of sheep scab as a notifiable disease in Britain in 1992, and the withdrawal of compulsory dipping, ovine psoroptic otoacariasis may now be more extensive within both pedigree and commercial flocks (Bates, 1996b).

In a survey of over 200 sheep presenting with active sheep scab, live sheep scab mites (*P. ovis*) were recovered from the EACs of 38.6% of infested sheep presenting with lesion areas ranging from 20.9% to 100% of body cover (Bates, 2002). Although the incidence of *P. ovis* otoacariasis increased the nearer the leading lesion edge approached the ears, 20.0% of sheep were infested in the EAC when the leading edge was as far away as the mid-back. In studies investigating the temporal progression of sheep scab, it was demonstrated that *P. ovis* migrated to the EAC as early as 28 days after artificial challenge, with the leading lesion edge 28.0 cm from the base of the ears (Bates, 2002). Unlike *P. cuniculi*, *P. ovis* isolated from the EAC can be infestive to the bodies of sheep. Acquired resistance to scab, as described earlier, may have a direct effect on the growth of sheep scab lesions originating from aural *P. ovis* (or from residual body mites in the regressed or cryptic phase of infestation) if these mites are to reinfest their previously infested host. Colonization would be more successful on scab-naive hosts.

Sheep scab was first recorded in Australia in 1788 and in New Zealand in 1840, and rapidly spread through the colonial flocks (Spence, 1951); it was eradicated from both countries through the slaughter of all infested animals (Kirkwood, 1986). It is assumed that the slaughter would have resulted in all reservoirs of *P. ovis* in the ear canals also being destroyed, a result that would have been impossible through a policy of plunge dipping. Ovine psoroptic mange (sheep scab) is not endemic to either Australia or New Zealand and *P. cuniculi* in the ears of goats is not therefore considered to be a reservoir of infestation. Similarly, an abattoir survey in Greece revealed 7% of sheep with *P. cuniculi* in the ears, even though sheep scab is relatively unknown in the country (Christodoulopoulos, 2006).

However, there is tentative evidence that aural *Psoroptes* could be responsible for spontaneous outbreaks of sheep scab. Following confirmation of foot-and-mouth disease (FMD) in the UK in 2001, a rigid quarantine strategy was imposed on a flock belonging to a British medical research institute, with no further contacts with other flocks, no new animals allowed on to the institute site and all staff required to take strict biosecurity measures. There had been no record of sheep scab previously at the institute. However, 511 days after the start of quarantine, five animals from the flock presented with active sheep scab (Bates and Gilbert, unpublished data). There were three possible sources of this infestation. The first (and obvious) source is that *P. ovis* was introduced to the flock with the last intake of sheep before the FMD quarantine, despite prophylaxis using doramectin. The second possible source of infestation could be a break in biosecurity. Here, transmission of infestation by shearing equipment is a possibility. However, because of the FMD restrictions, the only equipment supplied by the shearers were the handpieces, which were brand new and dipped in Virkon® disinfectant before use. The third possibility could be *Psoroptes* spp. mites in the ears of the sheep. This hypothesis would be hard to prove, and doramectin (even at 200 mcg/kg) should be effective in eradicating ear mites.

Seasonality

Ovine psoroptic otoacariasis is seasonal, with no mites recorded between late May and July (Bates, 1996b). This supports the observations of Heath *et al.* (1989), who noted a winter peak in New Zealand feral goats. Spence (1949) found that the ears were the most frequented cryptic site in the summer (82.5%), and that ear infestations often escaped detection and could only be demonstrated by post-mortem examination demonstrating large numbers of mites found in the EAC.

Transmission of ear mites

The spread of psoroptic ear mites may be direct (horizontal), through mutual grooming, playing, head butting, head shaking or close contact during sleeping or at feeding or drinking times. Mites could therefore enter flocks/herds via contact with infested sheep/goats at market, as well as through the purchase of infested stock. Transmission of *P. cuniculi* can occur vertically as well, soon after birth. Williams and Williams (1978) and Heath (1979) found mites present in the ears of 5-, 10–21-, 28-, 35- and 42- day- old goats.

P. cuniculi infestation appears to be a function of goat age. Bates (1992a) observed that the highest infestations (64.5%) were in animals from 6 to 12 months old, followed by animals from 12 to 18 months old (19.4%), animals from 1 to 6 months old (12.9%) and animals over 2 years old (3.2%). In contrast to the findings of Williams and Williams (1978) and Heath (1979), no mites were found in goats under 1 month old. Friel and Grainer (1988) observed that goats under 1 year old had a higher mite prevalence, but gross lesions were noted in only three animals.

Rams appeared to be the most affected with *P. cuniculi* in the ear, and in commercial flocks were often the only animals infested, therefore playing an important role in the epidemiology of otoacariasis (Bates,1996a), and potentially disseminating mites at tupping (mating). Studies by Liebisch *et al.* (1985) demonstrated that *P. cuniculi* could survive off the host for 84 days, and suggested that infested housing must be kept free from animals for at least 12 weeks.

Clinical signs

There are generally no gross clinical signs of caprine psoroptic otoacariasis, other than the occasional individual exhibiting ear scratching with the hind feet (Schillhorn van Veen and Williams, 1980; Heath *et al.*, 1983; Bates, 1992a). When exhibited, extreme clinical signs in goats include ear twitching (Cook, 1981) and head shaking (Lofstedt *et al.*, 1994). In Zimbabwe, Odiawo and Ogaa (1987) also recorded partial deafness, head tilting, recumbency, ear scratching and head shaking, walking in circles and occasional 'epileptiform fitting', and the ears could be thickened with their edges rolled up with thick keratinized painful areas together with dried bloody exudate.

The EAC of heavily infested goats can be plugged with thick, brown, laminated scab, sometimes completely occluding the canal, although damage to the tympanic membrane has never been recorded (Williams and Williams, 1978; Odiawo and Ogaa 1987). Heath *et al.* (1983) noted the occlusion of the auditory canal in 21% of goats examined. Cottew and Yeats (1982) also recorded that mites congregate at the base of the pinna and as well as the tympanic membrane. Caprine infestations have also been recorded to involve the entire pinna, or spread to infest the body, presenting lesions, severe pruritus and hair loss at the poll, neck, lips, muzzle, ears, withers, back, abdomen, pasterns and interdigital spaces (Littlejohn, 1968; Munro and Munro, 1980; Abu-Samra *et al.*, 1981; Lofstedt *et al.*, 1994). Infestations of the general body are more frequently seen in old or debilitated animals, with younger goats showing milder symptoms (Munro and Munro, 1980; Heath *et al.*, 1983). *P. cuniculi* is not considered to be a serious threat to goats, but in Angora goats it can inflict serious damage to the skin and hair and can be considered a threat to the Angora fibre industry worldwide (Graham and Hourigan, 1977).

Faccini and Costa (1992) recorded that the number of *Psoroptes* mites collected and

the mean numbers of mites per host were all considerably higher in goats (2390–15,224 mites collected) than in sheep (674–5729 mites collected). Goats therefore appear more tolerant to infestation than sheep, despite larger parasite burdens. In sheep, the symptoms of psoroptic otoacariasis differ both from those in goats and between lambs and adults (Bates, 1996b). In adults, the manifestations of the disease range from the asymptomatic to aural haematomae (Fig. 2.17), and violent head shaking and ear rubbing, leading to excoriation and wounding of the ear and ear base (Bates, 1996a). In lambs, symptoms include plaques of scab (often bloody) on the external ear cleft, excoriation of the ear base, ear scratching with the hind feet and inflammation of the external aspects of the horizontal canal (Bates, 1996a). In all cases, the internal pinnae are clear of the typical psoroptic scabs that are characteristic of mites in the cryptic phase. As in classical sheep scab, hypersensitivity is suspected to play a significant role, with infested animals exhibiting levels of pruritus ranging from negligible to extreme discomfort.

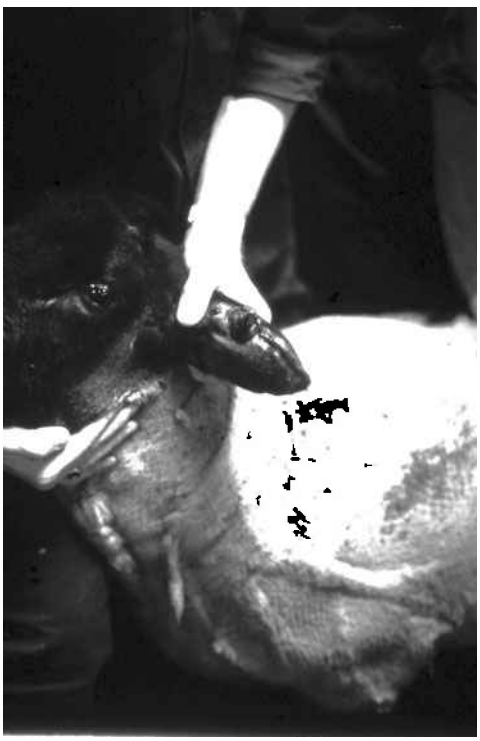

Fig. 2.17. Suffolk ram presenting with an aural haematoma resulting from infestation of the external auditory canal (EAC) by *Psoroptes cuniculi* (Photo © P. Bates).

Host specificity of Psoroptes ovis *and* Psoroptes cuniculi

The host specificity of *Psoroptes* spp. has been reviewed by Bates (1999a). *P. ovis* of sheep origin can infest cattle restrained from grooming, while retaining their infestivity to sheep. However, *P. natalensis* isolated from cattle does not appear to infest sheep. Psoroptic ear mites (*P. cuniculi*) have been isolated from goats, horses and domestic rabbits and are not infestive to the bodies of sheep, although mites isolated from the ears of rabbits have been shown to establish in the ears of sheep. *P. cuniculi* has not been isolated from wild rabbits.

The evidence for host specificity for on sheep and goat aural *Psoroptes* is equivocal. Sheep penned with goats heavily infested with *P. cuniculi* in the ears for 21 months failed to contract *P. cuniculi*, possibly as a result of the viscous nature of the sheep cerumen (Heath *et al.*, 1989). In Brazil, the prevalence of infestation and number of mites per host were all higher in goats than in sheep (Faccini and Costa, 1992). Consequently, there is a possibility that *Psoroptes* spp. may not be host specific and may freely transfer between the ears of sheep and goats given the correct set of circumstances (Sweatman, 1958; Williams and Williams, 1978). There is little evidence that goat *Psoroptes* spp. from the ear cause clinical sheep scab. Artificial and natural exposure of sheep to goats infested with *Psoroptes* spp. has never resulted in classical sheep scab (Sweatman, 1958; Williams and Williams, 1978; Heath *et al.*, 1989). This is supported by the fact that *Psoroptes* spp. are common in the ears of domestic and feral goats in Australia, New Zealand and the USA, where sheep scab has been eradicated and ovine psoroptic otoacariasis has not been recorded (Roberts, 1952; Williams and Williams 1978; Heath, 1979; McKenzie *et al.*, 1979; Schillhorn van Veen and

Williams, 1980; Cook, 1981; Hein and Cargill, 1981; Cottew and Yeats, 1982; Heath *et al.*, 1983, 1989; Friel and Grainer, 1988).

Evidence for the transfer of scab mites to goats is not so well documented. The hair coat of dairy goat breeds may not be suitable for maintaining the optimal microclimate for mite survival and thus colonization by *Psoroptes* mites. The long fibres of angora goats may be more conducive to mite survival. *Psoroptes* spp. mites are capable of causing serious damage to the skin and hair of angora goats (Graham and Hourigan, 1977) and are considered to be a threat to the angora fibre industry worldwide.

Psoroptes *spp. as vectors of disease*

Psoroptes spp. mites inhabiting the ears of goats have been shown capable of carrying mycoplasmal infections (possibly pathogenic) between goats (Cottew and Yeats, 1982; DaMassa, 1990).

***Chorioptes* (Psoroptidae)**

Mange caused by species of *Chorioptes* is more localized and often asymptomatic and is therefore not considered as serious as mange associated with *Sarcoptes* or *Psoroptes*.

Classification

Mites of the genus *Chorioptes* are obligate parasites of the bodies (and occasionally the ears) of herbivores (Fig. 2.18). *Chorioptes* spp. possess broad bowl-shaped suckers on very short unsegmented stalks (pedicels) (Fig. 2.19). There are only two recognized species of *Chorioptes*: *Chorioptes bovis* (infesting horses, cattle, sheep, goats and llamas) and *Chorioptes texanus* (infesting goats and cattle). Both species are identical in all stages except for the adult male, where there are differences in the lengths of the opisthosomal setae on the paired posterior processes (opisthosomae) (Baker, 1999).

World distribution

Chorioptes has been recorded infesting sheep and goats throughout the world. *C. bovis* was recorded as infesting the pasterns of sheep in the UK in the late 1960s, and was thought to have been eradicated following 20 years of compulsory dipping against sheep scab (*P. ovis*). However, chorioptic mange was recorded again in 2000 (Sargison, *et al.*, 2000) and is now common throughout the UK.

Life cycle

The complete life cycle (egg to egg) of *Chorioptes* takes approximately 3 weeks. Egg-laying females may live for only 3 weeks while non-laying females and adult males may live for up to 7–8 weeks. Females can lay a total of 3–17 eggs with an average of 9.5 eggs per female (Sweatman, 1957).

Host specificity

Infestation rates by *Chorioptes* spp. tend to be higher in goats than in sheep, with up to 80–90% of goats in individual herds being parasitized (Cremers, 1985).

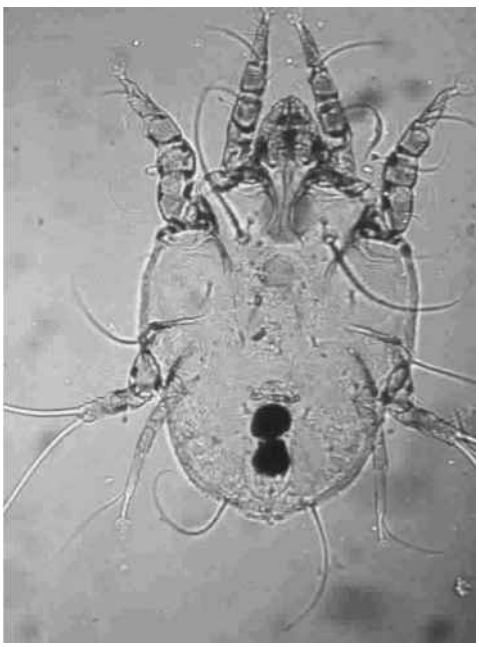

Fig. 2.18. Light microscope image of an adult female *Chorioptes bovis* (Photo © Crown Copyright 2011).

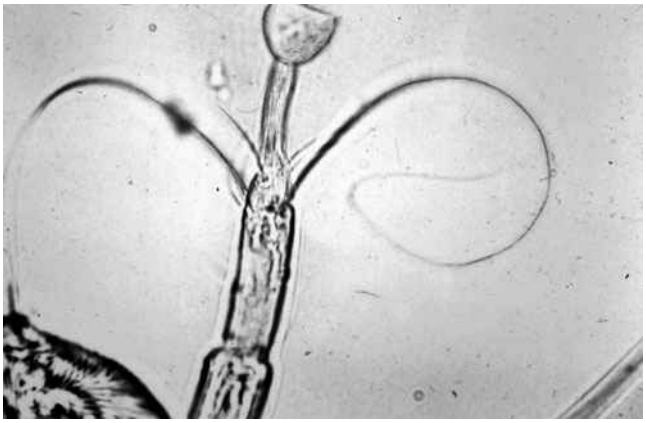

Fig. 2.19. The characteristic terminal, bell-shaped sucker (pulvillus) of *Chorioptes* spp. on a short, unsegmented pretarsus (peduncle) (Photo © Crown Copyright 2000).

Seasonality

Chorioptic mange in sheep and goats is found throughout the year but its occurrence is highest between February and March and lowest between August and September (Yeruham *et al.*, 1999).

Transmission

Infestation rates of 30–60% have been recorded in the USA, Europe, Australia and New Zealand. The prevalence of chorioptic mange is high in rams, particularly in 1- and 2-year-old animals, and can be spread by tupping. However, prevalence is always low in ewes (Heath, 1978). *C. bovis* can pass from ewe to lamb 6 weeks after birth (Heath, 1978). Studies by Liebisch *et al.* (1985) demonstrated that *C. bovis* could survive off sheep for 69 days, and suggested that infested housing must be kept free from sheep for at least 10 weeks. *C. bovis* can also be spread by direct contact of the feet with other parts of the body, notably the upper regions of the hind legs and scrotal areas of rams.

Feeding

Chorioptes mites do not pierce the skin, but have mouthparts that are adapted to feed on skin debris. They have been reared *in vitro* on epidermal material from a range of herbivores, including deer, antelopes, water buffaloes, zebus, zebras and donkeys (Sweatman, 1957).

Pathogenicity

Like psoroptic mange, chorioptic mange is a form of allergic dermatitis initiated by the mites themselves or by mite by-products.

Clinical signs

In goats, lesions can appear in the interdigital clefts, coronet, muzzle, eyelid, udder, scrotum and tail regions (Kusiluka and Kambarage, 1996). In sheep, lesions begin at the fetlock region and spread to the udder and scrotum (Kusiluka and Kambarage, 1996). Typically, *C. bovis* affects the forefeet, with mites occurring about the accessory digit and along the coronary borders of the outer hoof, often in clusters causing crusting primarily below the accessory digits and in the interdigital spaces (Kirkwood and Littlejohn, 1970; Mullen and O'Connor, 2009). Intense erythema in sensitized animals can lead to itching, restlessness, foot stamping, scratching and rubbing, often resulting in alopecia (Kusiluka and Kambarage, 1996). Overall, the allergic reaction can result in a yellow-brown lesion with haemorrhaging

fissures, particularly on the scrotal skin (Sargison *et al.*, 2000).

In heavily infested rams, the scrotal skin develops thick, yellowish, crusty layers, as much as 4.0 cm thick. In severe cases, elevated scrotal temperatures, attributed to the allergic response, can affect ram fertility. Rhodes (1976) observed severe seminal degeneration in rams with extensive chorioptic mange of the scrotum. The testes of affected rams had atrophied with the mean testicular weight for affected rams being 72 g (± 18 g) compared with 190 g (± 38 g) for unaffected rams. The seminiferous tubules of the atrophied testes were severely shrunken and spermatogenic arrest occurred at the spermatogonia or primary spermatocyte stage. The average testicular temperature was 0.6–3.1°C higher in affected rams. The exudative dermatitis does not penetrate the tunica vaginalis sac and had no effect on the general health of the rams. Rhodes (1976) concluded that scrotal mange causes testicular degeneration by raising the temperature of the scrotal contents.

The effect of chorioptic mange on semen quality depends on the size of the mange lesion; the presence of lesions of $<10\,cm^2$ in area has no obvious effect on semen quality when this is compared with that of unaffected rams (Rhodes, 1975). Conversely, semen quality was reduced in rams where lesions covered more than one-third of the scrotum. However, some rams with severe scrotal mange had good-quality semen while others presenting with relatively minor scrotal lesions had poor-quality semen (Rhodes, 1976). The condition is reversible, with normal spermatozoal production following treatment or spontaneous recovery (Rhodes, 1976).

Although sheep are commonly parasitized by *C. bovis* the small crusty lesions are hidden under the wool coat and are not usually noticed (Mullen and O'Connor, 2009). Most infested animals do not present with noticeable lesions or discomfort, even at relatively high mite densities, and many animals are asymptomatic and remain as silent carriers and a source of infestation.

Sarcoptes (Sarcoptidae)

Classification

Mites in the genus *Sarcoptes* are obligate parasites, burrowing into the skin of mammals. The itch mite *Sarcoptes scabiei* is the cause of scabies in humans and of mange in a wide range of domestic (including sheep and goats) and wild mammals throughout the world, generally affecting the sparsely haired parts of the body. The numbers of species within the genus is still open to debate. Studies of populations of *Sarcoptes* mites from a wide range of hosts have suggested that there is only one type species (*S. scabiei*), with a number of variants infesting a wide range of mammalian hosts (Fain, 1968). Recent investigations based upon molecular analysis of the ITS-2 (internal transcribed spacer-2) of the rRNA gene confirm that the genus *Sarcoptes* is monospecific (Zahler *et al.*, 1999).

Adult *Sarcoptes* are white, oval, 200–600 µm by 150–400 µm in size, with two pairs of legs anteriorly and two pairs posteriorly. Anterior legs are short and bear unjointed stalks with suckers. The posterior legs in females carry long bristles, not suckers (Fig. 2.20). In males, the third pair of legs also carries long bristles but the fourth pair has bristles. Posterior legs are rudimentary and do not extend beyond the border of the body.

World distribution

Sarcoptic mange (head mange, sarcoptic scabies) in sheep or goats, caused by *S. scabiei* var. *ovis* or *S. scabiei* var. *caprae* have been recorded in Europe, Africa, the Middle East, the Balkans, India and South and Central America. Sarcoptic mange in sheep has never been recorded in the UK.

Life cycle

Adult *S. scabiei* excavate into the horny stratum corneum of the skin, at a rate of 2–3 mm/day. Females are found at the end of burrows in the stratum corneum. The burrows contain faeces and relatively large eggs, which are laid singly. Eggs hatch after

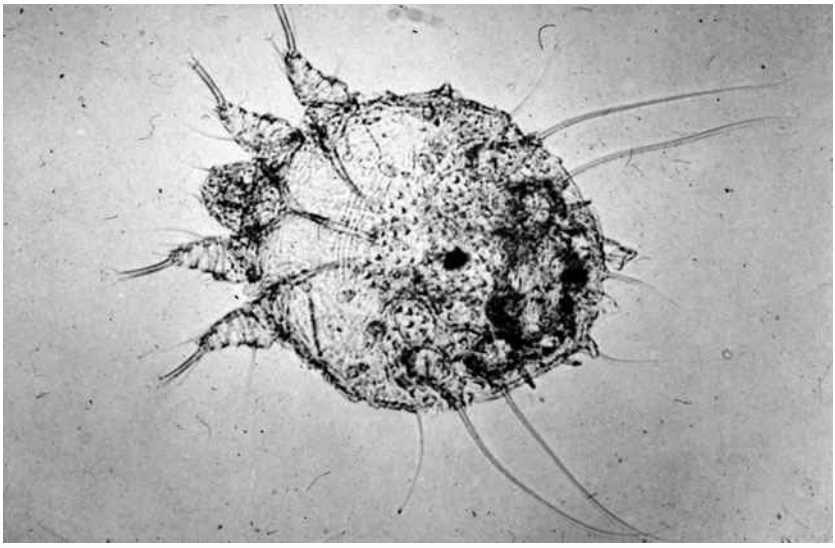

Fig. 2.20. Light microscope image of an adult female *Sarcoptes scabiei* (Photo © Crown Copyright 2011).

50–53 h. The larvae live on the surface of the skin, finding shelter and food in hair follicles. In 2–3 days, the larvae moult into protonymphs, which can also be found in the hair follicles. Protonymphs give rise to tritonymphs, which in turn moult into adult males or immature females. At this stage, both sexes are 250 µm long and are making short burrows (<1 mm) into the skin. Pairing probably occurs on the surface of the skin, and then the female makes a permanent burrow (at a rate 0.5–5 mm/day) using her chelicerae and the 'elbows' of the first two pairs of legs. Females take 3–4 days to become mature, increasing in size to 300–500 µm as their ovaries develop; they lay one to three eggs a day during a reproductive period lasting about 2 months. The total length of the life cycle from egg to egg is of the order of 10–14 days during which there is a mortality of about 90% (Mellanby, 1972).

Host specificity

In Saudi Arabia, *S. scabiei* has been shown to be transmitted through contact between sheep, goats, cattle, donkeys and dromedaries (Fayed *et al.*, 1991) and *Sarcoptes* isolates from goats (*S. scabiei* var. *caprae*) have successfully infested sheep (Ibrahim *et al.*, 1987).

Similar to observations made with *Psoroptes* spp., the progress of infestations can vary with sheep breed. Differences in the progress of clinical sarcoptic mange have been observed between Greek breeds of sheep, with the Chios (an indigenous dairy breed) appearing to be more resistant to *Sarcoptes* spp. than the introduced Friesian breed (Sotiraki *et al.*, 2001).

Effects of age and seasonality

Sarcoptic mange affects young animals more than adults, with more cases occurring in the autumn and winter. Mortality is higher in the colder winter months of the year (Ghimire *et al.*, 1998). In the Mediterranean, the incidence of clinical signs peak between November and March, particularly in sheep kept indoors in barns with high humidity (Christodoulopoulos, 2006).

Transmission and survivability off the host

The length of time that *S. scabiei* can survive off the host depends on the environmental conditions. Kraals (enclosures) in

South Africa previously occupied by infested goats were free from infestation when left unoccupied for 17 days (Du Toit and Bedford, 1932). Accommodation previously occupied by infested animals should therefore either be left in a dry state for 3 weeks or be treated with an acaricide (Radostits *et al.*, 1994). The spread of infestation among animals is by close contact and is facilitated by close herding or through family or social groups.

Feeding and pathogenicity

Sarcoptes spp. feed on cells and fluid of the germinal layer of the skin and are found on the sparsely haired parts of the body, such as the face and ears. Burrowing and feeding causes irritation, consequent scratching and associated inflammation and exudation, crust (scab) formation and alopecia. If left untreated, the skin wrinkles and thickens with the proliferation of connective tissue. Skin lesions in sheep involve hyperkeratosis and dermal lymphohistiocytic and eosinophilic infiltrations (Purcherea and Boulakroune, 1986). Lesions in other areas include the renal (congestion, perivascular lymphohistiocytic infiltrations) hepatic (lymphohistiocytic infiltrations of the portobiliary spaces) and pulmonary (dilation of the interalveolar capillaries) regions. Protein determination has shown a decrease in albumin, alpha-1 and alpha-2 globulins and an increase in beta-globulin (Purcherea and Boulakroune, 1986). Small foci of infection do not appear to affect the health of an animal adversely but they can be more serious if the condition spreads.

Clinical signs

The burrowing action of the mite can result in itching, partial or complete alopecia, redness, papules, exudation, scabs and crust – composed of keratinized, superficial epidermal layers and coagulated exudates (Christodoulopoulos, 2006). Alopecia is evident on the medial aspects of the rear limbs, axillae and brisket, and may extend to the abdomen, trunk, udder and teats (Kusiluka and Kambarage, 1996). Lesions start as dry, bran-like scales, later transforming into hard crusts. Cracks and fissures can appear on the infested skin (Kusiluka and Kambarage, 1996). The skin can be thickened and wrinkled, especially on the scrotum and pinnae. Usually the affected area is covered by thin white, dust-like scabs (Christodoulopoulos, 2006).

In sheep, *Sarcoptes* spp. prefer the haired areas, particularly the head, most commonly the dorsum of nose (Fig. 2.21). Other areas favouring infestation are the lips, mostly the upper lip, specifically the skin between the nostrils and the upper lip. Sometimes the external sides of ears can be

Fig. 2.21. Friesian ewe presenting with head mange caused by *Sarcoptes scabiei* var. *ovis* (Photo © Smaro Sotiraki).

infested. Less frequently lesions can be found on supraorbital or the periorbital areas and the poll. In severe cases, lesions may involve the whole head. Mites sometimes infest the feet, sternum and abdomen, and rarely colonize woolled areas (Christodoulopoulos, 2006). Excoriations are also present, mostly at the base of ears as a result of extensive scratching using the hind legs. Scratching can result in aural haematomas and traumatic keratoconjunctivitis. In extreme cases, pyoderma may occur as a result of bacterial contamination (Christodoulopoulos, 2006).

Notoedric mange

Notoedres cati (commonly found on cats and dogs) has been recorded infesting small ruminants in sub-Saharan Africa (Kusiluka and Kambarage, 1996).

Forage mites (Acaridae)

Sheep scab is a form of allergic dermatitis caused primarily by the mite's excretory products, including guanine. Guanine is the major nitrogenous excretory product of all acarines – mites, ticks, spiders, etc. Thus, skin exposure to large numbers of forage (tyroglyphid) mites from infested feed, hay or straw can result in skin lesions very similar to sheep scab in susceptible sheep.

The most obvious characteristic of the more common forage mites is the possession of many 'hairs' that are much longer than in the parasitic forms, and may be simple, branched or spatulate (Fig. 2.22). In some genera (e.g. *Glycyphagus*) the posterior hairs often become entangled in debris. *Acarus siro*, probably the commonest of these mites, has shorter hairs. Mites in the genera *Acarus* or *Tyrophagus* can occur in very large numbers in hay and straw bales, and these often increase to extremely large numbers over the autumn.

Forage mites were identified in 23.9% of skin scrapings submitted to the VLA during the Sheep Scab Eradication Campaign in the UK (1974–1992) (Bates, 2009a). The majority of infestations were associated with housed sheep and were either exclusive or mixed with *Psoroptes ovis*. Active motile non-parasitic forage mites, or their immobile deutonymphs (hypopi), have also been isolated from the auditory canals of 47/2516 (1.9%) sheep investigated for *P. cuniculi* (Bates, 1996a).

Sancassania berlesei (= *Caloglyphus berlesei*) is common in stables and causes a serous dermatitis under loose wool, but with little itching. Barton *et al.* (1988) recorded infestations of *S. berlesei* in merino hoggets in Australia. The skin of the withers and down the flanks appeared thickened and was exuding sufficient serum to keep the fleece overlying the lesion wet. Close examination revealed masses of pale pink mites clustered on the skin and extending into the fleece, which gave off a strong ammoniacal smell. Infestations were progressive and mites were able to transfer to other wet sheep. Once established, mites were capable of causing sufficient skin damage to allow copious amounts of exudates,

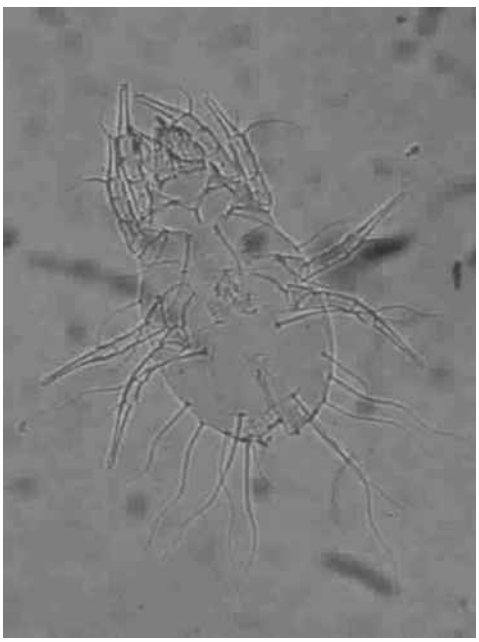

Fig. 2.22. Light microscope image of a free-living forage mite (Photo © Crown Copyright 2011).

thus wetting the fleece and maintaining the optimal microclimate.

Animal housing and feed troughs should be cleaned thoroughly after turnout, and old feed, hay and straw must be disposed of. As well as causing dermatitis, the ingestion of large numbers of forage mites can also lead to gastrointestinal disturbances.

Prostigmatid Mites

Psorobia (Psorergatidae)

Adult *Psorobia* (*Psorergates*) *ovis*, the sheep itch mite, can be recognized by the radial arrangement of their legs around a more or less circular body, each leg having an inward curving spine on each femur.

World distribution

Psorobia ovis appears to affect only merino sheep and has been reported in Argentina (Baker, 1999), Australia (Johnson *et al.*, 1989a), New Zealand (Baker, 1999), Nigeria (Baker, 1999), South Africa (Soll and Carmichael, 1988), and the USA (Baker, 1999), where it is present in many flocks, but is generally asymptomatic.

Life cycle

Female *P. ovis* lay few eggs in their lifetime. Larvae are immobile, as they have reduced legs. Three nymphal stages follow, with the legs becoming progressively larger with each moult and, by the adult stage, the legs are well developed and the mites are mobile. Single mites occur in cavities under the stratum corneum, mostly in parts covered in wool, but also on the legs and face. Adults and tritonymphs may occur on the skin surface. Adults of both sexes are very small (200 μm) and the life cycle is completed in 4–5 weeks.

Seasonality

P. ovis is sensitive to direct sunlight and drying, and so the lowest populations are seen in the summer; populations increase steadily during autumn, winter and spring.

Transmission and survivability off host

Adult *P. ovis* are very sensitive to desiccation, dying within 24–48 h when removed from their host. Transmission occurs during the brief period after shearing. Considerable mortality of mites has been observed up to and including day nine after shearing, which suggests that fluctuations of temperature and solar irradiation following shearing create considerable stress for the *P. ovis* population, and that the first 2 weeks after shearing could be an appropriate time for control. *P. ovis* can also spread from ewe to lamb at suckling. Transmission can be prevented by not holding recently shorn sheep in the yards any longer than normal.

Pathogenicity

P. ovis is found under the stratum corneum in the superficial layers of the skin of the sides, flanks and thighs, feeding on the exuding fluid. Affected sheep may become 'tolerant' after 1–2 years, but can still remain infested. Infestations spread slowly and may affect 10–15% of sheep in a neglected flock.

Clinical signs

The infested area is dry and scurfy, wool fibres break easily, with the remaining wool coming together as ragged tufts. Irritation causes the sheep to rub and kick (rather than bite) the affected area, resulting in pulled wool and 'fleece derangement' (especially on the sides of the body and flanks) and downgrading of the wool clip (Johnson *et al.*, 1990b). Most fleece damage is found along a line drawn from the elbow to the hip – the area where the sheep can concentrate rubbing or bite.

Demodex (Demodicidae)

Demodectic mange (demodecidosis, follicular mange, red mange) is caused by the mites of the genus *Demodex*. *Demodex* spp. are minute, annulate, worm-like, parasitic mites with short legs (Fig. 2.23).

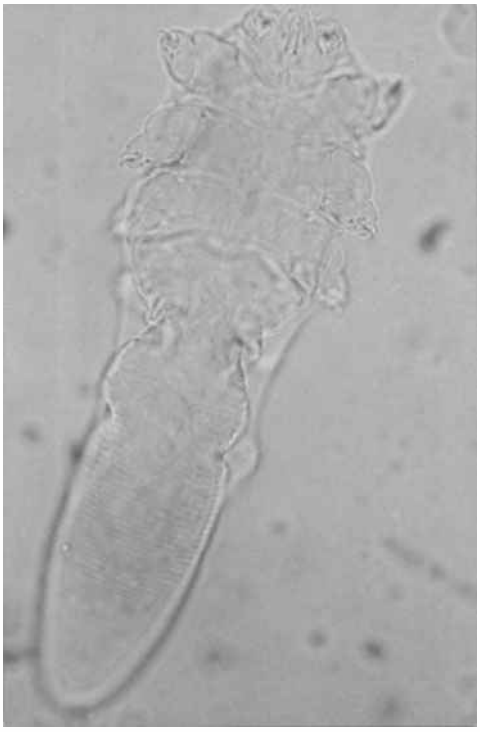

Fig. 2.23. Light microscope image of a *Demodex* spp. mite (Photo © P. Bates).

Two species of *Demodex* have been isolated from sheep: *Demodex aries*, an innocuous commensal of the follicles and sebaceous glands of the feet, face, eyelids, ears, prepuce and vulva; and *Demodex ovis*, which lightly parasitizes the hair follicles and sebaceous glands of primary hairs over the entire body, with the highest populations occurring on the neck, flanks and shoulders (Desch, 1986). Goats can be infested with *Demodex caprae*.

Life cycle

The hexapod larvae have short legs ending in a single trifid claw. An unusual feature of the life cycle of *Demodex* is a second hexapod form, designated a protonymph, with legs also terminating in a pair of trifid claws. The deuteronymph stage that follows is octopod, moulting into the adult (Baker, 1999).

Host specificity

Demodex spp. are strictly host specific with no records of interspecific transfer of any species. Certain breeds of goat (e.g. Saanen) tend to be more sensitive to *D. caprae* than other breeds.

Transmission and survivability off the host

Transmission of *D. caprae* to newborn goats typically occurs within the first days following birth. Other possible means of transmission are parental licking and intimate contact with infested animals during mating.

Feeding

Demodex spp. feed by pushing their needle-like cheliceral digits through the epithelium and sucking out the contents of the underlying cells.

Pathogenicity and clinical signs

Clinical signs can be severe in goats infested with *D. caprae*. Infested follicles become distended with mites, mite exuvia, eggs and epithelial cells, forming papules. Papules usually appear on the face, neck, axillary region or udder, with a few to several hundred lesions per animal (Mullen and O'Connor, 2009). Papules are easily palpable in the skin, and pyogenic bacteria may enlarge them into nodules up to 4.0 cm in diameter, as mites multiply within. Ruptured nodules tend to suppurate, contributing to the transmission of mites via exudates to other goats. As in dogs, goats have a high incidence of general demodecidosis that can involve almost the whole body (Mullen and O'Connor, 2009). If the nodules rupture internally, granulomas develop while phagocytic giant cells of the goat host engulf and destroy the mites (Mullen and O'Connor, 2009). As individual nodules disappear, others are formed. Skin with advanced lesions is thick and scaly, alopecic, nodular or pustular. Itching may stimulate kicking, biting and rubbing of the lesions. In general the disease is of low incidence and of little importance. However, in some instances death can occur (Radostits *et al.*, 1994).

On sheep, *Demodex* spp. can be present without obvious clinical signs (Carter, 1942). Lesions are sometimes present around eyes, nose and on the ears. In merino sheep groups of fibres can be glued together down their length, with the tips matted and reddish brown (Chapman, 1973). There can be an offensive odour, similar to that of red mange in dogs. Microscopic examination of the matted wool can reveal numerous individuals of *Demodex* (as eggs, nymphs and larvae) along the wool fibre (Chapman, 1973).

Harvest mites (Trombiculidae)

Harvest mites (Trombiculidae) are prostigmatid mites that are parasitic in the larval stage ('chiggers') and free living in the nymph and adult stages as predators on the eggs and/or young of other arthropods. Over 1200 species of trombiculids have been described, with at least 50 attacking humans or livestock. Trombiculids are widely distributed and can cause a trombidiosis, a dermatitis due to the feeding of trombiculid larvae. Species of harvest mite recorded as attacking sheep and goats include harvest bugs (*Neotrombicula autumnalis*) in Europe, chiggers (*Eutrombicula alfreddugesi, Neoschongastria americana*) in America and scrub itch mites (*Eutrombicula sarcina*) in Australia.

Trombiculid larvae are just visible to the naked eye and appear yellowish, orange or red; they can often be seen in the centre of the skin lesions they induce (Mullen and O'Connor, 2009). In Europe, clinical signs of infestation in sheep and goats by *N. autumnalis* include pruritus, scabs and alopecia, particularly around the head and neck (Mullen and O'Connor, 2009). In Australia, sheep have experienced severe dermatitis on the legs and feet caused by infestations of *E. sarcina*, a mite that usually infests kangaroos (Mullen and O'Connor, 2009). An orf-like condition in sheep caused by *Guntheria* spp. has been reported during the summer months in South Africa (Otto and Jordaan, 1992).

Trombiculids probably breed throughout the year, but in cooler regions the number of generations per year is limited and seasonal, e.g. larvae of *N. autumnalis* are abundant in late summer or autumn (hence harvest mites) (Kettle, 1995).

Life cycle

Female mites deposit spherical eggs in damp but well drained soil. The 250 µm long larvae ascend grass stems to a height of 60–80 mm to await passage of a suitable host on to which they cling. Larvae are picked up on the faces and legs of grazing animals (Kettle, 1995). Larvae attach by their chelicerae and partially digest the tissue with saliva, pumped in and out, which leads to the formation of a feeding tube (stylostome) in the host at the point of larval attachment (Kettle, 1995). The mite feeds for several days before falling off and entering a quiescent phase before moulting into the protonymph. There are three nymphal stages, but only one (the second) is active. The adult mite is 1 mm long and its body is 'waisted', producing a figure-of-eight shape (Kettle, 1995).

Mesostigmatid Mites

Raillietia (Halarachnidae)

Raillietia spp. are oval mites, about 1 mm long, with a small oval dorsal plate. Two species are recognized: *Raillietia caprae* (syn. *Raillietia manfredi*) infesting the ear canals of goats in Australia, Brazil, Mexico and Venezuela, and of sheep in Brazil (Baker, 1999), and *Raillietia auris*, which although a parasite of cattle has been recorded in the ears of sheep in Brazil (Fonseca *et al.*, 1983) and Iran (Rak and Naghshineh, 1973). In Mexico, 30.5% of goats examined were shown to be infected in the auditory canal by *R. caprae* (Quintero *et al.*, 1987).

Raillietia spp. feed on epidermal cells and wax, but not blood (Kettle, 1995). Infestations are generally subclinical. Postmortem examination may reveal increased cerumen and a reddish aspect of the tympanic membrane (Fonseca *et al.*, 1983).

Other clinical findings include caseous plaques in the ear canal (40%), petechiae in the mucosa of the auditory canal (20%) and perforation of the tympanic membrane (2%) (Quintero *et al.*, 1987). Mixed infestations with *P. cuniculi* have been observed, but only in goats (Fonseca *et al.*, 1983).

Zoonoses

Sarcoptes scabiei originating from small ruminants have also been recorded infesting humans, presenting as a dermatitis of the forearm (Purcherea and Boulakroune, 1986).

A survey of human scabies in the north Sinai region of Egypt found 8.7% of those examined to be infected with *S. scabiei* (8.1%) and *Psoroptes ovis* (0.63%) (Mazyad *et al*, 2001). The infestation with *S. scabiei* was higher in shepherds (79.7%) than in non-shepherd patients (20.3%).

Workers handling infested stored food can develop allergic reactions to forage mites and suffer from pruritus, dermatitis, rhinitis or asthma (Walker, 1994).

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3

Ticks (Ixodida)

The Order Metastigmata – or Ixodida, within the subclass Acari, constitutes the ticks (Ixodida), relatively large acarines, which are blood-sucking ectoparasites, and feed off a diversity of vertebrate hosts. Over 850 species have been described worldwide.

Morphology

Tick mouthparts (gnathosoma) consist of a movable capitulum consisting of the basis capituli, paired four-segmented palps, paired chelicerae and a ventral median hypostome, armed with rows of backwardly directed teeth which securely attach the tick to its host. The genital opening and anus are both located ventrally, the genital opening being at the level of the second pair of legs and the anus a little posterior to the fourth pair of legs. Haller's organ, used in host seeking, is located on the tarsus of the first pair of legs (Kettle, 1995).

Classification

Ticks are arranged in three families: (i) the Ixodidae (hard ticks) is the largest family, and consists of 13 genera and 650 species; (ii) the Argasidae (soft ticks) consist of five genera and approximately 170 species; and (iii) the Nuttalliellidae, with only a single species (Kettle, 1995).

Over 100 different tick species belonging to 11 different genera have been recorded infesting sheep worldwide (Liebisch, 1997). Apart from the damaging effects of infestation (Kok and Fourie, 1995), many of these ticks are also vectors of tick-borne disease agents (Tatchell, 1977; Uilenberg, 1997) or can cause paralysis (Gothe, 1984).

The argasids are tough, leathery ticks in which there is little differentiation between the sexes. In nymphs and adults the capitulum is not visible from the dorsal view, being located ventrally in a recess (the camerostome) (Fig. 3.1). The fourth segment of the palp is similar in size to the other three. When eyes are present they are lateral in position in folds above the legs. The stigmata are small and placed anterior to the coxae of the fourth pair of legs (Fig. 3.1). The pad-like pulvillus between the claws is either absent or rudimentary (Kettle, 1995).

In the ixodids, sexual dimorphism is well developed and ixodid ticks possess a dorsal scutum (shield), which is absent in argasid ticks. The dorsal scutum is small in the female and almost covers the entire dorsal surface in the male (Fig. 3.2).

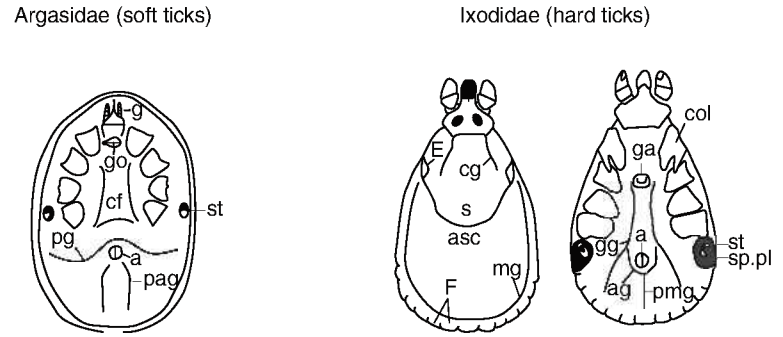

Fig. 3.1. Major external features of adult female Argasidae (soft ticks) and Ixodidae (hard ticks). a, anus; ag, anal groove; asc, alloscutum; cf, coxal fold; cg, cervical fold; col, coxa I; E, eye; F, festoons; g, gnathosoma (capitulum); ga, genital apron; gg, genital groove; go, genital opening; mg, marginal groove; pag, postanal groove; pg, preanal groove; pmg, postanal median groove; s, scutum; sp.pl, spiracular plate; st, stigma.

Fig. 3.2. *Ixodes ricinus*. The capitulum (mouthparts) of the female (left) is considerably longer than that of the male (left). The dorsal scutum is small in the female and almost covers the entire dorsal surface in the male (Photo © Crown Copyright 2011).

The capitulum is terminal and always visible when the tick is viewed from above. When eyes are present, they are located dorsally at the sides of the scutum. The fourth segment of the palp is reduced and recessed on the ventral surface of the third segment. The stigmata are large and posterior to the coxae of the fourth pair of legs. The pulvillus is well developed (Kettle, 1995).

Ixodid and argasid ticks also differ in many aspects of their biology. In the Ixodidae there is a single nymphal stage. The adult female engorges, develops a very large batch of eggs which she lays and then dies. In contrast, in the Argasidae there are several nymphal stages, and the adult female feeds several times during her lifetime and lays several batches of eggs. Ixodid ticks feed on the host for a number of days. Argasids, with some exceptions, are nocturnal and visit the host to feed for a period of minutes (Kettle, 1995).

Soft Ticks (Argasidae) Infesting Sheep and Goats

The spinose ear tick (*Otobius megnini*)

Otobius megnini, the spinose ear tick, has been recorded from a number of hosts in North America that include sheep and goats (Cooley and Kohls, 1944); this tick has also been recorded from sheep in India (Chellappa and Alwar, 1972). *O. megnini* is associated with stables and animal accommodation. The female tick lays her eggs in cracks and crevices in the walls several feet above ground, and this behaviour ensures that the emerging larva is at a height to transfer easily to the bodies of large, stabled domestic animals (Kettle, 1995).

Life cycle

Eggs hatch in 11 days in the summer, and in 3–8 weeks under cooler conditions (Nuttall *et al.*, 1908; Bedford, 1925a). The eggs are small, oval and reddish in colour. The hexapod larva is 0.5 mm in length. Its terminal capitulum is very long, accounting for more than one-third of the length of the unfed larva. There are two pairs of ocellus-like eyes present dorsally (Cooley and Kohls, 1944). The larva enters the ear of its host, where it engorges and may attain a length of 4 mm (Nuttall *et al.*, 1908). Larval engorgement takes 5–10 days and is followed by a quiescent period before the moult to the octopod nymph.

There are two nymphal stages, which are characterized by having the capitulum on the ventral surface and a spiny integument. Nymphs reattach to the skin lining of the ear, suck blood and remain in the ear for an unusually long time. Most nymphs leave the host within 5 weeks but they may remain for several months (Bedford, 1925a). The fully fed nymph measures up to 8 mm long. Nymphs drop off the host and find their way into cracks and crevices in walls and woodwork, under stones or under the bark of trees, usually low down, where the second-stage nymph moults to an adult 1–4 weeks later (Walker *et al.*, 1978). The body of the adult is fiddle shaped and is constricted posterior of the fourth pair of legs. The adult does not feed, and its hypostome is poorly developed and without teeth (Kettle, 1995).

O. megnini can persist in empty stables for more than 2 years (Walker *et al.*, 1978). Unfed larvae usually survive for less than a month, but under favourable conditions can survive for as long as 4 months. Female *O. megnini* can wait up to 18 months to be impregnated and then lay up to 1500 eggs in small batches over a period of a few weeks to several months. Infestations of *O. megnini* cannot be eradicated by vacating premises unless for excessively long periods (Kettle, 1995).

O. megnini does not transmit pathogens but does considerable damage to the ears, eardrums and auricular nerves by feeding. The ear can be choked with ticks, wax and other debris, and the eardrum can be ruptured, which favours secondary infections. Badly infested sheep and goats may die, and loss of condition in infested animals is common (Bedford, 1925a).

Ornithodoros

Ornithodoros lahorensis is a serious pest of sheep in Asia, the southern republics of the former USSR and south-eastern Europe from sea level to 2900 m (Kettle, 1995). In the Urmia district of Iran, 2.6% of sheep have been shown to be infested with *O. lahorensis* (Yakhchali and Hosseine, 2008).

When *O. lahorensis* larvae find a host they remain on it for 3–6 weeks, engorging four times and moulting three times. The engorged nymph detaches and drops to the ground where it moults into an adult. Given the opportunity, the adult will feed rapidly on another host, after which females will deposit batches of 300–500 eggs. This species is facultatively autogenous and can mature two batches of eggs without a blood meal. Unfed adults can live for 18 years and larvae for a year (Hoogstraal, 1985).

Hard Ticks (Ixodida) Infesting Sheep and Goats

Hard ticks (Ixodida) possess terminal mouthparts (the 'capitulum') and a dorsal shield (the 'scutum'). The shield is small in the female and almost covers the entire dorsum of the male. Seven genera of hard tick have been recorded infesting sheep and goats worldwide.

Ixodes

Ixodes is the largest genus within the hard ticks, and comprises over 300 species highly specialized in their habitats with species parasitizing land mammals, bats and seabirds. They are small, inornate ticks, easily overlooked when searching a host.

The capitulum of the female is considerably longer than that of the male (Fig. 3.2). The second segment of the palp is often constricted at the base, creating a gap between the palp and the mouthparts. There are no eyes or festoons. The anal groove passes anteriorly to the anus and *Ixodes* is said to be prostriate. In other genera, the anal groove is either posterior to the anus or obsolete (metastriate). In the male, there are seven ventral plates including a median row of three – pregenital, median and anal, a pair of adanals and a pair of epimerals. The margins of the epimerals, which are placed posterolaterally, are often indistinct (Arthur, 1965).

In the UK, there are three important species of *Ixodes*: *Ixodes ricinus* (the 'castor bean tick', 'sheep tick' or 'pasture tick'), *Ixodes hexagonus* (the 'woodland tick' or 'hedgehog tick') and *Ixodes canisuga* (the 'dog tick'), all of which can be found feeding on sheep and goats.

Ixodes ricinus is a parasite of temperate regions of Europe (Gray, 1991) and North Africa. Although the tick has been known to be present in the British Isles since Viking times, the first detailed study of the species took place in Britain in the 1930s (Arthur, 1963), mostly in relation to hill sheep farming.

Ixodes rubicundus is a common tick species in sub-Saharan Africa (Kusiluka and Kambarage, 1996). *Ixodes holocyclus* can be a cause of tick paralysis in Australia.

Haemophysalis

There are 155 easily recognizable species in the genus *Haemophysalis*. These are small, inornate ticks with short mouthparts (i.e. brevirostrate). The basis capituli is rectangular and the base of the second palpal segment is expanded, projecting laterally beyond the basis capituli. The second and third palpal segments taper anteriorly so that the capitulum anterior to the basis capituli appears to be triangular. There are no eyes in either sex and no ventral plates in the male. Festoons – uniform, rectangular areas along the posterior margin of the body – are present, separated by grooves. They are best seen in unfed specimens and are lost in engorged females.

Haemophysalis punctata has limited distribution in the UK, infesting sheep in the southern and western coastal areas (north Wales, Sussex, Kent, etc.). *Haemophysalis inermis* has been recorded infesting sheep (but not goats) in southern Europe.

Boophilus

The five species of the one-host tick, *Boophilus*, are small, inornate, brevirostrate ticks in which the anal groove is absent. The basis capituli is hexagonal dorsally, and there are simple eyes laterally on the scutum. Ventrally, coxa I is bifid, and there are paired adanal and accessory adanal plates flanking the anus posteriorly.

Boophilus spp. ticks have been recorded infesting small ruminants in northern India (Umesh and Sharma, 2003) and Ethiopia (Yacob *et al.*, 2008), and 1.3% of goats presented at an abattoir near Abuja, Nigeria were shown to be infested with *Boophilus* spp. ticks (Idris and Umar, 2007). *Boophilus decoloratus* has been recorded infesting sheep and goats in sub-Saharan

Africa (Kusiluka and Kambarage, 1996), and 2.4% of sheep in the Urmia district of Iran were shown to be infested with *Boophilus annulatus* (Yakhchali and Hosseine, 2008).

Rhipicephalus

Rhipicephalus spp. are small, metastriate, brevirostrate, reddish or blackish-brown ticks that are mostly inornate. The basis capituli is hexagonal dorsally and eyes and festoons are present. Coxa I is bifid in both sexes. The male has adanal and accessory adanal plates on the ventral surface.

These ticks have been isolated from sheep and goats in Italy, Ethiopia (Yacob *et al.*, 2008) and northern India (Umesh and Sharma, 2003), and from 4.7% of goats presented at an abattoir near Abuja, Nigeria were shown to be infested with *Rhipicephalus* spp. ticks (Idris and Umar, 2007). The predominant species infesting small ruminants in Iran appears to be *Rhipicephalus bursa*, with 91% of sheep and 89% of goats in the Urmia district shown to be infested, while 7% of sheep and 11.4% of goats were infested with *Rhipicephalus sanguineus* (Yakhchali and Hosseine, 2008). In sub-Saharan Africa, *Rhipicephalus evertsi*, *Rhipicephalus appendiculatus* and *Rhipicephalus lunulatus* have been recorded infesting small ruminants (Kusiluka and Kambarage, 1996). The 'red-legged' tick (*R. evertsi evertsi*) can induce paralysis in lambs, and heavy infestations may also damage the udder and induce blowfly strike (Fourie *et al.*, 2001).

Dermacentor

The 30 species of *Dermacentor* are medium to large, usually ornate, metastriate, brevirostrate ticks. The basis capituli is rectangular dorsally and eyes and festoons are present. Coxa I is bifid in both sexes and Coxa IV is generally enlarged in the male which has no ventral plates.

Dermacentor spp. have been recorded infesting sheep and goats in southern Europe, northern India (Umesh and Sharma, 2003) and Britain. *Dermacentor reticulatus* has been recorded in south-west England and north Wales. *Dermacentor andersoni* and *Dermacentor variabilis* can be responsible for cases of tick paralysis in North America.

Hyalloma

The 29 species and subspecies of *Hyalloma* are medium-sized metastriate ticks, with long mouthparts, i.e. they are longirostrate. The basis capituli is subtriangular dorsally and eyes are present. Festoons and ornamentation of the scutum are variable characters which may be present or absent. The male has one pair of adanal plates, and accessory adanal plates may or may not be present. Coxa I is bifid. *Hyalloma* spp. are tough, hardy ticks which survive where humidity is low, climatic conditions extreme, hosts rare and hiding spaces sparse.

Hyalloma spp. ticks have been recorded infesting small ruminants in northern India (Umesh and Sharma, 2003) and 1.0% of goats presented at an abattoir near Abuja, Nigeria were infested with *Hyalloma* spp. ticks (Idris and Umar, 2007). *Hyalloma detritum* has been recorded infesting sheep but not goats in southern Europe and *Hyalloma truncatum* in sub-Saharan Africa (Kusiluka and Kambarage, 1996). In the extensive sheep-rearing areas of South Africa 'bont-legged' ticks (*Hyalloma* spp.) can cause severe abscesses at the site of attachment. Damage to the udder, lameness and the potential for blowfly strike often result from such lesions (Kok and Fourie, 1995).

Amblyomma

The 102 species of *Amblyomma* are large, ornate, metastriate, longirostrate ticks with eyes and festoons, but no adanal plates in the male.

Amblyomma spp. ticks have been recorded infesting small ruminants in northern India (Umesh and Sharma, 2003) and Ethiopia (Yacob *et al.*, 2008), and 1% of goats presented at an abattoir near Abuja, Nigeria were infested with *Amblyomma* spp. ticks (Idris and Umar, 2007). In sub-Saharan Africa, *Amblyomma variegatum* and *Amblyomma hebraeum* have been recorded infesting small ruminants (Kusiluka and Kambarage, 1996).

Life cycle

Ixodid ticks pass through four life stages (instars) – egg, larva, nymph and adult.

The majority of ixodid ticks are referred to as three-host ticks, with each motile stage feeding on a different host (dependent on size). However, *Boophilus* spp. are one-host ticks, in which engorged larvae and nymphs do not drop off the host but remain attached to moult *in situ*, and the subsequent stage reattaches to the same host. A few species have adapted to a two-host cycle in which the larva and nymph occur on the same individual host, and the nymph then drops off and the adult parasitizes a different individual of the same or another host species. Included in the two-host ticks that parasitize domestic animals are *R. evertsi*, *R. bursa*, *Hyalloma marginatum* and *H. detritum* (Hoogstraal, 1978), all recorded to infest sheep and goats.

The life cycle of *I. ricinus* is typical of the three-host ticks. Adult *I. ricinus* only feed successfully on larger mammals (ewes, cows, horses, deer, etc.) (Milne, 1949). Larvae and nymphs generally feed on lambs, but can be found feeding on ewes. The proportions of the different life stages feeding on sheep have been recorded as larvae 50%, nymphs 80–90% and adult females 94.4–99.2%. Unfed nymphs and, to a greater degree, unfed females are relatively sparse in distribution; thus, the host that covers the most ground in areas where the microclimate is suitable for tick survival (i.e. hill sheep in Britain) will pick up the most ticks (Milne, 1949). Each tick stage feeds approximately every 12 months, giving a 3 year life cycle from egg to adult (Ross, 1988), although this can take 2–6 years to complete (Gray, 1991).

Eggs

A fertilized female tick drops off the host and seeks a sheltered situation in which to develop and lay a single large batch of eggs, after which she dies (Fig. 3.3). Egg batches may contain several thousand brown, globular eggs and oviposition may continue for several days. Each egg receives a wax coating from a special organ (the Gené's organ) as it leaves the genital opening. If eggs do not receive this coating they will dehydrate. In general, eggs hatch into larvae within 2–36 weeks (Soulsby, 1982), but under natural conditions (in Ireland) periods of 16–48 weeks and 21–28 weeks have been recorded for spring and autumn feeding ticks, respectively (Gray, 1991).

Larvae

Larvae have six legs and are very small and difficult to see when unfed. They attach and feed for several days before engorging and dropping off. Larvae breath through their skin, therefore water loss is exclusively through their cuticles. If larvae are not successful in finding a new host they return to the more humid layers near the ground, where at suitable humidities they are able to take up water from the environment (Sonenshine, 1993). In this way, larvae can survive for considerable periods unfed.

Nymphs

Fed larvae digest their blood meal and moult into the eight-legged nymphal stage. Nymphs breathe through a spiracle/tracheal system, which makes them susceptible to desiccation. They feed for 4–8 days on the host, engorging more rapidly towards the end of this period, before dropping off the host to find a suitable location in which to digest their blood meal and moult into the adult stage.

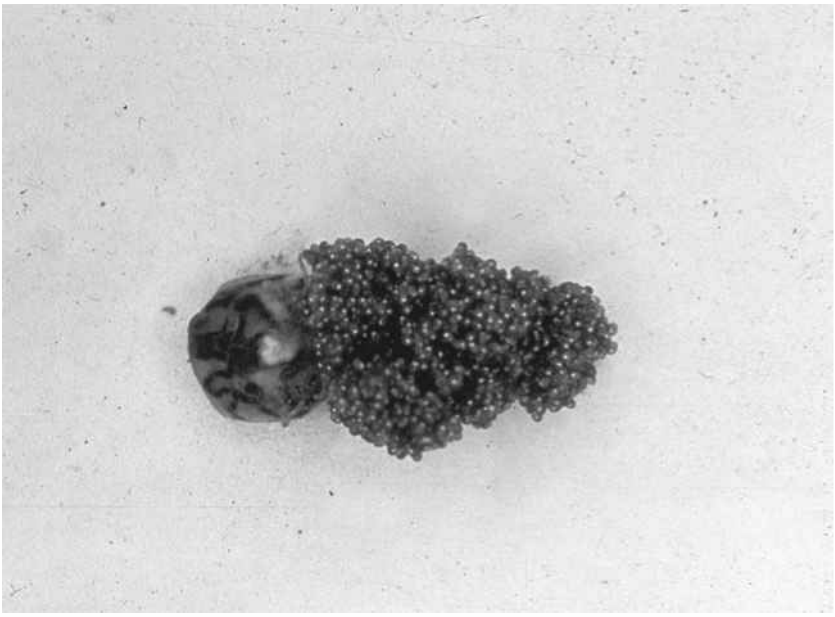

Fig. 3.3. A fertilized female tick with egg batch (Photo © Crown Copyright 2011).

Adults

When an adult female finds a suitable host she attaches and engorges; however, adult males feed but do not engorge. The engorged female drops off the host and hides away in a suitable location to digest the blood meal and lay an egg batch. The tick may travel several metres in a month away from the point of drop-off, before coming to rest (Cerny, 1959). Only one or two adult ticks survive from each egg batch to lay eggs themselves.

Mating

I. ricinus mates on or off the host. Males are readily attracted to a pheromone emitted by virgin females that acts as both an assembly and a sex pheromone (Cerny, 1959). In Ireland a large proportion of female ticks mate in the vegetation rather than on the host (Gray, 1987). During mating, the mouthparts of the male are used to stimulate the female before spermatophore transfer. In *Ixodes* spp. the mouthparts (hypostome and chelicerae) of the male are inserted into the genital opening of the female. The male transfers spermatids in a spermatophore. Males can copulate 20–30 times (Oliver, 1989).

Host specificity

Ixodes spp. are not entirely host specific, but most occur on a limited range of hosts, concentrating on particular parts of its body and adjusting to the seasonal and daily cycles of the host behaviour. In Ethiopia, ticks (*Amblyomma*, *Hyalloma* and *Rhipicephalus*) are significantly more common on sheep (31.7%) than on goats (18.6%) (Yacob *et al.*, 2008). Wild animals can act as reservoirs of infestation.

Seasonality

When not feeding on a host, each tick stage can be found in the undergrowth, where they are exposed to variations in microclimate – the thicker the vegetation, the heavier the tick burden. High humidity is essential. If the relative humidity falls below 80% for prolonged periods or in areas prone to flooding, survival is difficult (Lees, 1946a). These requirements restrict *I. ricinus* to deciduous woodland containing small mammals and deer, but in areas with sufficient rainfall large populations may occur in open habitats and

moorland, where the majority of them feed on livestock (Milne, 1949). Ticks are on the increase in the UK. Factors driving this increase include changes in farming practices (e.g. countryside stewardship), climate change and acaricide resistance.

Tick populations are extremely dependent on the weather and are, therefore, seasonal. Three-host ticks such as *I. ricinus* attach and feed at times of the year when there is sufficient warmth and a lower risk of desiccation, with active peaks in the spring and autumn. The duration of these peaks is determined by the tick stage and the climatic conditions at the time.

In the UK, the numbers of adult *I. ricinus* peak in the spring (between February and March) with a smaller late summer/autumn peak (between July and November). Nymphs are found throughout most of the warmer months of the year (February to October) but there is a definite peak in numbers in late summer/autumn (July to November). Larvae peak in the spring (April to August) with a second significantly larger peak in numbers in the late summer/autumn (July to October). However, in recent years, this bimodal pattern has been reduced to one peak for each instar from February to November. Thus a population in an infested area can comprise both resting and feeding generations coming in or out of synchrony (Ross, 1988). Diapause is a form of resting, with a decreased level of metabolism slowing down growth, development and reproduction. Diapause greatly improves survival during unfavourable conditions. Ticks in diapause are more resistant to starvation, drought and adverse temperatures. Other UK tick species, such as *D. reticulatus*, are active well into the winter and can be found in very large numbers on a single host feeding on both the fleeced and non-fleeced areas of sheep.

Finding a host

In the UK, *I. ricinus* activity is triggered by an increase in day length, but the temperature must also exceed +7°C (Ross, 1988). The active tick moves down the humidity gradient by climbing vegetation. In vegetated areas, larval ticks climb vegetation and accumulate at the tips of grasses and similar plants.

Ticks detect the approach of a host using sensory receptors in Haller's organ, which is located on the tarsus of the first pair of legs, and they seek a suitable host by waving those legs in the air ('questing'). Sensory receptors in the anterior pit of Haller's organ detect odour (particularly phenolic odours), while other receptors detect temperature, humidity and ammonia. Receptors in the posterior capsule detect carbon dioxide, odours and temperature. Other sensors on the tarsus detect phenolic compounds (which are produced in large quantities by feeding females as sex pheromones) and still others detect temperature gradients and respond to the host's body heat.

Larvae tend to quest in clumps and not move far from the site of hatching. Nymphs and adults are more randomly distributed within a pasture. Unfed ticks may quest for several weeks, but there is a limit to the amount of energy they can expend. After four failed questing attempts the tick can die (Ross, 1988); generally, ticks do not survive from one season to the next without a blood feed (Gray, 1991).

Feeding

Once on the host, sensory receptors on the tarsi and palps provide information to enable the tick to find a suitable site for attachment (Waladde, 1987). A stimulation period of approximately 4 h is required by an adult *I. ricinus* before feeding commences (Ross, 1988). During this period, there is a risk of desiccation, as the early stages of feeding are accompanied by major cuticular changes.

A hungry tick selects a site where capillaries are close to the surface and lifts its body by 45° – with its head pointing downwards. The barbed hypostome then pierces the skin – with no pain to the host (Fig. 3.4). Salivary secretions open up the lesion, allowing the hypostome to be gradually worked into the skin. Eventually the hypostome is cemented into place. Secretions provoke an inflammatory response, creating a feeding pool. Blood and

exudates are sucked from the feeding pool into the tick gut. There are alternate periods of sucking and salivation (within a minute), interspersed with periods of inactivity. Ticks remain attached until the meal is complete. In *I. ricinus* this can be 2–15 days depending on instar, species, host and site of attachment. Adult males feed only sparingly. A total increase in body size by 100× during feeding is an underestimate, as a lot of excess fluid is returned to the host as saliva (Fig. 3.5).

Fig. 3.4. Scanning electron microscope image of the barbed hypostome of *Ixodes ricinus* (Photo © Crown Copyright 2011).

Site preference

Different tick species have different predilections for sites. *Ixodes* ticks rarely attach to the back or upper flanks in large mammals, but these sites are frequently parasitized in smaller animals. On larger mammals, *Ixodes* ticks attach to the facial region, ears, snout, axillae and groin, usually decreasing in numbers from the fore part of the body to the hind (Arthur, 1963). In South Africa, adult *Hyalloma* spp. and *Rhipicephalus* spp. preferentially attach to the anogenital, udder and groin regions, or other body regions on the ventral aspects of the sheep (Howell *et al.*, 1978; Kok and Fourie, 1995). In Iran, hard tick (ixodid) infestations were observed to occur mostly on the fat tails of sheep (55.8%) and the tails of goats (96.3%), with an average of 2.5 ticks per sheep and 4.3 per goat. The heaviest infestations were observed on female sheep and goats (Yakhchali and Hosseine, 2006). *Hyalloma* spp. ticks (particularly *H. truncatum*) attach to the interdigital clefts and the fetlocks of lambs, often causing lameness (Kok and

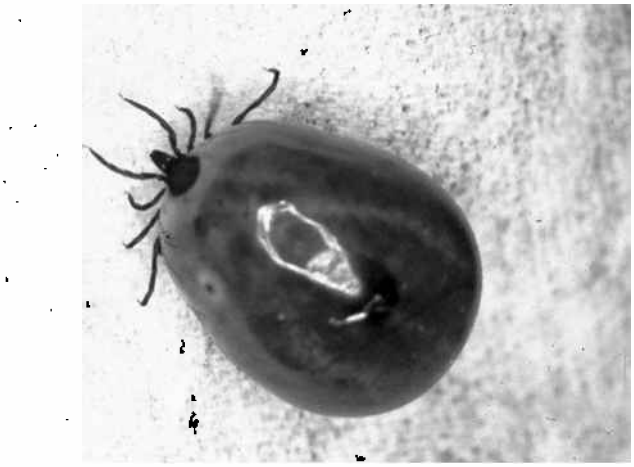

Fig. 3.5. Fully engorged female *Ixodes ricinus* (Photo © Crown Copyright 2011).

Fourie, 1995). Control is therefore difficult, particularly in the case of the use of pour-on formulations (Fourie *et al.*, 2001).

Host resistance

Acquired resistance to tick infestation can develop and is characterized by reduced feeding times, engorged body weights and egg output. Vaccines have been developed against the one-host cattle tick *Boophilus microplus.* However, UK tick species have multiple hosts and vaccines are unlikely to be developed.

Adverse Effects of Tick Infestations

Adverse effects of tick feeding can include paralysis, lameness and transmission of disease, and heavy infestations can result in anaemia and death. Once a tick has detached from the host, the site of attachment may continue to bleed, attracting opportunistic blood-feeding or secretophagous fly species that may infect the old bite lesion and possibly predispose to blowfly strike.

Tick paralysis

Tick paralysis is an acute, ascending, flaccid motor paralysis that can be fatal, particularly in the case of paralysis of the respiratory muscles (Kusiluka and Kambarage, 1996). Tick species associated with paralysis include *I. ricinus, I. holocyclus* (Australia), *I. rubicundus* (South Africa), *D. andersoni* (western North America), *D. variabilis* (eastern North America) and *Ornithodoros* spp. (Kettle, 1995; Kusiluka and Kambarage, 1996).

Paralysis is associated with the feeding of a female tick and the first symptoms occur 5–7 days after attachment; 'a single female tick suffices to completely paralyse and kill an adult human' (Gothe *et al.*, 1979). Except in the case of *I. holocyclus*, physical removal of the attached tick terminates the condition and allows complete recovery (Sonenshine, 1993), but with *I. holocyclus* physical removal of the tick may worsen the symptoms (Stone, 1988). The toxin secreted by *I. holocyclus* (holocyclotoxin) is secreted by specific cells in the salivary glands.

I. holocyclus is present in moist, vegetated habitats along the eastern coast of Australia. Its principle hosts are bandicoots, but it will attach to a wide range of hosts, including livestock. Bandicoots are not greatly affected by the paralysing toxin as the majority become immune to its effects. In South Africa, tick paralysis was first recognized in sheep in 1890. The major species involved are *I. rubicundus* and *R. evertsi evertsi. I. rubicundus*, the karoo paralysis tick, is estimated to cause around 30,000 deaths a year in livestock, mainly sheep (Spickett and Heyne, 1988). Tick paralysis due to *R. e. evertsi* occurs primarily on sheep and goats, and its severity is related to the number of female ticks that have engorged (Sonenshine, 1993). Tick species associated with paralysis in goats in South Africa include *I. rubicundus* and *Rhipicephalus warburtoni* (Fourie *et al.*, 1988; Fourie and Horak, 1991; Fourie *et al.*, 1992).

Lameness

Intense lameness in goats has been recorded where ticks are attached around the coronary band (Kusiluka and Kambarage, 1996). In South Africa, *A. hebraeum* and *Rhipicephalus glabroscutatum* are associated with foot abscesses in goats (MacIvor and Horak, 1987).

Disease vectors

Each tick instar blood feeds only once – three times throughout the entire life cycle. This is a fundamental difference from blood feeding insects such as mosquitoes or midges, which can feed many times as an adult and in which interrupted feeding is common. The main diseases that are carried by ticks are described below.

Tick-borne fever

Tick-borne fever (TBF), caused by *Ehrlichia phagocytophila* (*Anaplasma phagocytophila, Cytocetes phagocytophila*). As already described in Chapter 2, this is a benign rickettsiosis of domestic and wild ruminants, characterized by minimal observable effects, despite large numbers of parasites in the blood and a high fever. Pregnant animals may abort and records of abortion in 50% of breeding stock introduced from tick-free areas have been cited (Anon., 1988). However, the important effect of this disease is immunosuppression, which in sheep can lead to secondary infections, including lamb pyaemia caused by *Staphylococcus aureus*, septicaemia caused by *Pasteurella haemolytica* (*trehalosi*), and infections by parainfluenza-3 virus, louping ill and *Chlamydia psittaci* (Brodie *et al.*, 1986). Cell-mediated immune response as measured by a delayed skin hypersensitivity is not affected by TBF, suggesting that immunosuppression in TBF is probably due to the effect of *E. phagocytophila* on the cells mediating the humoral immune response (Batungbacal and Scott, 1982). A transient lymphocytopenia has been reported to develop and lambs so affected have been shown to be defective in their ability to produce antibodies (Batungbacal and Scott, 1982) and to mount cell-mediated responses (Brodie *et al.*, 1986). Larsen *et al.* (1994) demonstrated experimentally that levels of antibody against tetanus toxoid or influenza virus produced by TBF-infected sheep were significantly lower than in control sheep. TBF infection may impair both primary and secondary responses for up to 6 weeks. Immunosuppression by TBF may also complicate sheep management in areas where TBF is enzootic by interfering with response to immunization (e.g. clostridial vaccines) (Batungbacal and Scott, 1982).

In the UK, ticks infest both upland areas of grazing and also lower land used mainly for beef or dairy enterprises, where TBF and redwater fever (babesiosis) have been recorded in cattle (Cranwell and Gibbons, 1988). Nearly all tick areas support the presence of TBF, in contrast to louping ill and redwater fever, which are absent from some tick-infested areas (Lamont, 1983).

The main foci for both sheep scab (*Psoroptes ovis*) and TBF are the upland common grazing areas of Britain and, owing to the need for antibody production to control scab infestations, immunosuppression by TBF may have profound effects on the progress of the disease.

Louping ill

Louping ill is an acute viral disease of the central nervous system (CNS) affecting most species of domestic livestock and man. In sheep, the disease is most frequently seen in lambs and shearlings, and is associated with ataxia, incoordination, paralysis, convulsions, coma and death within 24 and 48 h (Reid, 1983). There is a school of thought that *E. phagocytophila* is capable of disrupting the vasculo-meningeal barrier of the CNS, thereby rendering the sheep vulnerable to louping ill virus. The virus may be introduced to the bloodstream via the bite of an infected tick, but it cannot pass this barrier to attack the nerve cells and so produce the typical nervous symptoms (Anon, 1988). It has been shown that both *E. phagocytophila* and the louping ill virus frequently exist together in ticks found on farms where louping ill is common. It is probable under natural conditions that the majority of adult sheep on such farms have been infected with TBF and have recovered (Anon, 1988).

Tick pyaemia

A lowered resistance, as a sequel to TBF, appears to allow the agent of lamb pyaemia (*Staphylococcus aureus*), which is normally present on the skin and mucous membranes, to invade and produce a bacteraemia with the consequential tendency for abscesses to develop in the joints and internal organs ('tick pyaemia' or 'cripples'). Tick pyaemia is a disease of young lambs and is considered to be a serious loss of production in many UK hill flocks.

Q fever

Q fever (caused by *Coxiella burnetti*) is another rickettsial disease affecting British livestock; the Veterinary Laboratories Agency (VLA) recorded 24 cases in sheep and 33 cases in cattle between 1995 and 2005. *C. burnetti* is a rare cause of abortion in sheep and is transmissible to man (Scott, 1983). Tick species capable of transmitting Q fever include *Dermacentor marginatus*, *H. punctata*, *I. ricinus*, *R. sanguineus*, *R. bursa*, *H. marginatum* and *Hyalloma anatolicum* (Liebisch, 1979), although ticks are only one of many potential routes of transmission. Q fever can be transmitted to man by rubbing contaminated tick faeces into a (tick-bite) wound. Veterinary surgeons, abattoir workers and farmers are traditionally most at risk of infection.

In Europe, there are three epidemiological zones of Q fever. These are the southern endemic zone; a zone into which the infection is repeatedly introduced; and a northern zone, which remains free from the infection (Liebisch, 1979). Q fever becomes endemic in a zone where suitable tick vectors are present. A systematic study of the tick fauna was carried out by Liebisch (1979) in the then Federal Republic of Germany, where all three of these zones are found. *D. marginatus* was the species responsible for the existence of complete natural foci of Q fever in the south of the country. The distribution of this tick and the seasonal activity of the adults attacking sheep were the same as the seasonal incidence of Q fever. The slaughtering of serologically positive reactors remains a successful method of control in northern Germany, where incomplete foci of the infection occur, while in the south more than 20% of sheep have been recorded to be infected and control methods must include control of the vector (Liebisch, 1979).

Heartwater

Heartwater (cowdriosis), caused by *Ehrlichia ruminatum* (*Cowdria ruminatum*) is an important constraint to small ruminant husbandry and production in much of sub-Saharan Africa (Woldehiwet, 2007). Transmission is generally by ticks of the genus *Amblyomma*. In susceptible breeds, sheep infection can be acute or peracute with high mortality rates, particularly in sheep brought in from non-endemic regions. In West, East and Central Africa the principle vector is *Amblyomma variegatum*, and in South Africa it is *Amblyomma herbeum* (Woldehiwet, 2007). In Ethiopia, Kenya and Sudan, *Amblyomma lepidum* and *Amblyomma gemma* are the major vectors. Heartwater is also present in some Caribbean islands, including Guadaloupe (Woldehiwet, 2007).

Nairobi sheep disease

Nairobi sheep disease (NSD) is a tick-borne viral disease of small ruminants in East and Central Africa transmitted primarily by *Rhipicephalus* spp. (Woldehiwet, 2007). NSD (family *Bunyaviridae*, genus *Nairovirus*) is characterized by fever, diarrhoea and high mortality. A related disease, caused by Ganjam virus, causes infections in sheep, goats and humans in India. NSD virus is both transovarial and transtadial in the tick vector (Woldehiwet, 2007). *R. appendiculatus* is considered to be a major vector in Kenya and Uganda but *Rhipicephalus simus* and *Rhipicephalus pulchellus* have also been associated with NSD in some regions in East Africa (Woldehiwet, 2007).

Ovine anaplasmosis

The tick-borne disease anaplasmosis, caused by *Anaplasma ovis* and *Anaplasma mesaeterum*, is a benign but persistent rickettsiosis of sheep and goats endemic to tropical and subtropical Africa, Asia, parts of southern and central Europe and the western USA (Stoltz, 1994). Infected animals remain as carriers of infection for life. *A. ovis* is more widespread and considered to be more pathogenic to sheep. *A. mesaeterum* was recently recognized, mainly in Europe, and appears to be more pathogenic to sheep than goats. *A. ovis* is antigenically and genetically related to the bovine pathogen *Anaplasma marginale* (Woldehiwet, 2007).

Malignant theileriosis of small ruminants

The benign form of the protozoal disease theileriosis in sheep has a wide distribution, with *Theileria ovis* present in Europe, the Middle East, Africa and parts of Asia, while *Theileria seperata* is known to be present only in Africa. *Haemophysalis punctata* is a known vector of *T. ovis*. The more virulent species, *Theileria lestoquardi*, is endemic to the Middle East and is probably present in regions of North Africa and parts of China where bovine theileriosis caused by *T. annulata* is endemic (Woldehiwet, 2007). In susceptible indigenous sheep moved from non-endemic to endemic areas, losses from malignant theileriosis can be as high as 40%, and they can be even higher in imported exotic sheep (Woldehiwet, 2007).

Ovine babesiosis

Babesiosis, a protozoal disease caused by *Babesia ovis*, *Babesia motasi* and *Babesia crassa* in sheep and goats, is widespread in most tropical and subtropical countries and in Europe and the Middle East (Uilenberg, 2001). Babesiosis is transmitted vertically and transtadially by ticks of the genera *Rhipicephalus*, *Dermocentor*, *Ixodes* and *Haemophysalis*. Adult sheep and goats are more susceptible to infection than lambs or kids (Woldehiwet, 2007).

Lyme disease

Ixodes ricinus acquired new significance in the early 1980s as a vector of Lyme disease (or Lyme borreliosis, a bacterial disease caused by *Borrelia* spp.) in humans (Burgdorfer *et al.*, 1982). In 1993, a questionnaire survey of three moorland recreational areas of England (Dartmoor, the Quantock Hills and the North York Moors) showed extremely low levels of knowledge of the disease, its mode of infection and measures that might reduce the risk of tick bites (Sheaves and Brown, 1995). Although sheep and goats are not directly affected by *Borrelia burdorferi*, they can be considered as amplifying hosts for the tick vector populations, particularly within the hill sheep populations in the moorland-based national parks of the UK.

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Lice (Phthiraptera)

Lice are parasitic insects, characterized by a body distinctly divided into head, thorax and abdomen with three pairs of legs originating from the thorax in all instars (life stages).

Mammalian lice (Phthiraptera) can be divided into the chewing lice (Mallophaga), erroneously called 'biting' lice which feed on skin debris and can be identified by their wide heads (with the musculature and mouthparts necessary for this method of feeding), and the blood-sucking lice (Anoplura) which can be identified by their relatively narrow heads.

All lice are morphologically adapted to a parasitic life through dorsoventral flattening, a horizontal (prognathous) head with mouthparts directed forward, reduction in the number of antennal segments, and thoracic and abdominal spiracles. Infestations of sheep or goats by lice (pediculosis) are found throughout the world.

Mallophaga (Chewing Lice)

Mallophaga (chewing lice) consist of two broad groups: (i) the Amblycera; and (ii) the Ischnocera. In amblyceran lice, the antennae are recessed in antennal grooves from which the last segment may protrude, whereas in the Ischnocera the antennae are quite obvious. The Amblycera and Ischnocera – collectively known as the Mallophaga ('wool eaters') – have over 2600 species described; the majority (85%) are ectoparasites of birds and feed on feathers, hair and other epidermal products.

Two species of chewing louse infest sheep: (i) the cosmopolitan *Bovicola ovis* (formerly *Damalinia ovis*); and (ii) the less common *Bovicola peregrina*, which has been recorded infesting sheep in South Africa (Fourie and Horak, 2000). Domestic goats can be infested with the chewing species *Bovicola caprae* (Kettle, 1995), and fibre-producing angora goats can be infested with the red louse, *Bovicola limbata* and the less common *Bovicola crassipes*.

All species of *Bovicola* isolated from sheep or goats (as well as cattle or equids) are morphologically similar (Fig. 4.1 shows *B. ovis*), and specialist keys are required to differentiate them to species level.

The sheep chewing louse (*Bovicola* (*Damalinia*) *ovis*)

The chewing (or body) louse of sheep, *Bovicola* (*Damalinia*) *ovis*, is a small, pale to red/brown insect with a broad head and chewing mouthparts. Adult *B. ovis* are 1.8 mm long and 0.6 mm wide.

Fig. 4.1. Light microscope image of the chewing louse *Bovicola ovis* (Photo © Crown Copyright 2000).

B. ovis probably occurs in all sheep-producing countries but, with the exception of wool-producing Australia and New Zealand, attracts little attention. This is reflected in the numbers of scientific publications on *B. ovis* originating from these two countries over the last 50 years. *B. ovis* is a common ectoparasite of sheep in Australia, with a distinct increase in prevalence recorded in recent years (Morcombe *et al.*, 1994) which is strongly correlated with changes in the Wool Market Price Indicator and the failure to eradicate lice from flocks. These failures are partly a consequence of the reduced use of insecticidal treatments, the development of synthetic pyrethroid (SP) resistance and an increase in the transmission of lice between flocks (Morcombe *et al.*, 1994). In 2004, the apparent prevalence of flocks infested with lice in South Australia was calculated to be 21%, with 13% infested in high rainfall areas, 21% in the cereal/sheep zone and 25% in the pastoral zone (James and Riley, 2004).

B. ovis is known to occur in the USA, but its distribution has not been documented (Durden and Lloyd, 2009). The louse has been reported as absent from Wyoming (one of the USA's major sheep-rearing states) for 40 years and is uncommon, if not absent, from the neighbouring states of Montana and Nebraska (Durden and Lloyd, 2009). The control of *B. ovis* in the UK has in the past been an adjunct to the compulsory scab dip in autumn *(Psoroptes ovis),* and these ectoparasites were almost eradicated from mainland UK. Pockets of infestation remained on some Scottish islands and isolated areas of Dartmoor, the Lake District and the Pennines. There has been a recent increase in the prevalence of *B. ovis* since the lifting of compulsory sheep scab dipping in 1992, and lice have now become prevalent on nearly all hill grazings in the UK (Bates, 1999b). In 1997, Uruguay abandoned compulsory dipping for the control of lice and scab, and since then the prevalence of *B. ovis* has increased and many stock owners have returned to dipping in diazinon (Mari, personal communication). Lice are also a significant problem in Argentinian Patagonia and, to a lesser extent, in the Pampas and Mesopotamia areas of Argentina (Bulman, personal communication).

The goat chewing louse (*Bovicola* (*Damalinia*) *caprae*)

Bovicola caprae, which is similar in morphology to *B. ovis*, has been recorded infesting short-haired dairy goats in the UK (Rankin, unpublished observations), and is probably widespread throughout the world.

The red louse (*Bovicola* (*Damalinia*) *limbata*) of angora goats

The red louse (*Bovicola limbata*) (which, like *B. caprae*, is similar in morphology to *B. ovis*) is an important parasite of

angora goats in Britain (Bates *et al.*, 2001a), Argentina (Olaechea, personal communication) and South Africa (Fourie, personal communication). Heavy infestations can lead to discomfort, often resulting in loss of weight, lowered vitality, and a reduction in fibre yield and/or quality (Peterson and Bushland, 1956).

Measurements, using scanning electron microscopy, have demonstrated that *B. limbata* is 35% larger than the chewing louse of dairy goats (*B. caprae*). The mean body length, body width and head width of *B. limbata* are 1603 µm, 740 µm and 491 µm, respectively, while corresponding mean measurements for *B. caprae* are 1177 µm, 516 µm and 381 µm (Bates *et al.*, 2001a).

Anoplura (Blood-Sucking Lice)

Anopluran lice are 0.5–8.0 mm long as adults, and have highly specialized mouthparts that are not visible externally. The lice possess a single claw which, when retracted, makes contact with a thumb-like process on the tibia; the enclosed space has the same diameter as the hair of the host, which enables the louse to stay attached to an active host.

Sheep can be infested with three species of sucking louse: the face louse (*Linognathus ovillus*), the foot louse (*Linognathus pedalis*) and *Linognathus africanus*; all three have been recorded infesting sheep in South Africa (Fourie and Horak, 2000). Domestic goats can be infested with the blood-sucking lice *L. africanus* and *Linognathus stenopsis.*

Like *Bovicola* spp., *Linognathus* spp. isolated from sheep or goats are morphologically similar (Fig. 4.2), and specialist keys are required to differentiate to species level.

The African blue louse (*Linognathus africanus*)

L. africanus is an ectoparasite of both sheep and goats and, although originally described in Africa, is distributed worldwide (Durden and Lloyd, 2009). The species has not been recorded in the UK (Bates, unpublished data). In the USA, it has been reported from the southern and south-western states. Recently, it has established in the sheep-producing areas of several western states, where it has become a major pest of sheep (Durden and Lloyd, 2009). The female *L. africanus* is 2.2 mm long and the males are 1.7 mm long.

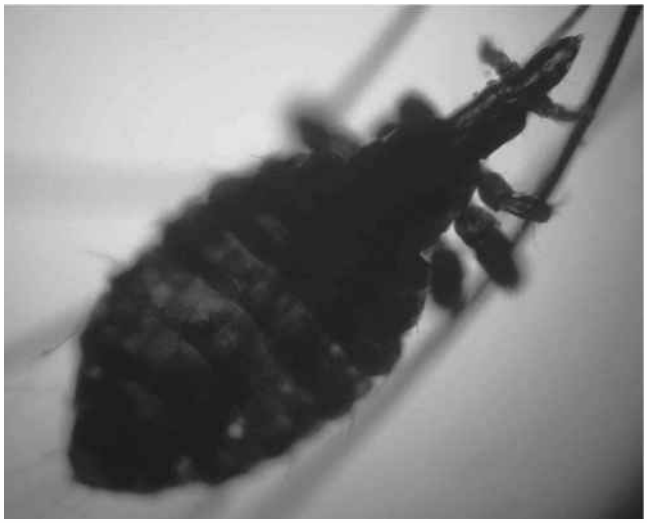

Fig. 4.2. Light microscope image of the sucking louse *Linognathus* spp. (Photo © Youngs Animal Health).

The sheep face louse (*Linognathus ovillus*)

The face louse or blue body louse (*L. ovillus*) has been recorded infesting sheep in Australia, France, New Zealand, the USA, the UK and probably all other sheep-rearing countries. In Tasmania, *L. ovillus* has been observed more frequently in recent years, presumably as a result of the popularity of pour-on treatments for body lice (*B. ovis*), which have no claimed effect against *L. ovillus* (Butler, 1986).

L. ovillus can be found on both the haired and woolled areas of the face. As populations increase, infestations can spread over the woolled skin of the entire body. Dense accumulations of *L. ovillus* on the face can discolour white hair or wool to a definite grey.

The sheep foot louse (*Linognathus pedalis*)

The foot louse *L. pedalis* is morphologically similar to *L. ovillus*, and has been recorded in Africa, Australia, the USA and South America. Like foot mange (*Chorioptes ovis*), the foot louse may have succumbed to former annual compulsory scab dipping and has not been recorded in the UK for at least 20 years.

The goat sucking louse (*Linognathus stenopsis*)

L. stenopsis has been recorded infesting short-haired dairy goats in the UK (Rankin, unpublished observations) and probably infests goats throughout the world.

The Louse Life Cycle

All lice (Anoplura and Mallophaga) exhibit incomplete metamorphosis. Eggs hatch into nymphs – small editions of the adult that live and feed in the same way.

Eggs of the sheep chewing louse (*B. ovis*) are 1.8 mm long and 0.6 mm wide, and are individually cemented to wool fibres; they hatch after 1–2 weeks. Adults can live for up to a month on the host (laying approximately 30 eggs) (Kettle, 1995). In *B. ovis*, there are three nymphal stages, lasting 7, 5 and 9 days, respectively. Each nymphal stage undergoes a moult, and the final nymphal stage moults into the adult. Freshly moulted nymphs or adults are pale brown (almost white), but they change to a darker red/brown as the cuticle becomes sclerotized. Adult female and male *B. ovis* can live for 27 and 48 days, respectively. The minimum length of the *B. ovis* life cycle is 34 days. The optimal environment for *B. ovis* reproduction is a temperature of 37.0°C and a relative humidity of 70–90%. *B. ovis* is susceptible to extremes in temperature and humidity, and the lice move up and down the wool fibre to accommodate changes. On hot days, the fleece temperature on exposed parts of a sheep with a fleece length of below 25 mm can range from 45°C near the skin to 65°C at the wool tip. In anatomical areas of low temperature (e.g. legs and tail), oviposition is inhibited. At a fleece thickness of 3.0–10.0 cm most eggs are laid within 6 mm of the skin surface, even when the fleece is 10.0 cm deep; few eggs are laid more than 12 mm from the skin surface. In fleeces where the temperature ranges from 38°C at the skin surface to 15°C near the tip of the fleece, 69% of the mobile population (nymphs and adults) are within 6 mm of the skin surface and only 15% more than 12 mm from the skin.

Host Specificity

Lice demonstrate a high degree of host specificity. Where they do occur on more than one host, the hosts themselves are closely related (e.g. sheep and goats) – and the host specificity of goat and sheep chewing lice is open to question, with cross-infestations reported, although these are unlikely to be common occurrences. Studies in Australia have demonstrated that blood sucking and chewing goat lice can survive on sheep for 5–7 days but will not reproduce (North, 2004). Further studies in Australia have reported that *B. ovis*

can survive and apparently breed on angora cross goats penned with lousy sheep (Hallam, 1985). However, chewing lice of angora goats (*B. limbata*) do not appear to be infestive to sheep. Small numbers of live angora lice (*B. limbata*) were observed on a Saanen dairy goat over 4 months of exposure to infested angoras, but these did not establish permanent colonies and were not observed once the Saanen goat was isolated from further exposure; *B. limbata* were never observed on similarly exposed sheep (Bates *et al.*, 2001a). The blood-sucking lice *L. stenopsis* and *L. africanus,* which are generally found on short-haired dairy goats, have also been recorded infesting angora goats and sheep (Bates, 2001a).

Seasonality

Strong seasonal cycles in *B. ovis* numbers have been observed in ewes; numbers increase through the winter and spring and decline during the summer (Scott, 1952; Kettle and Pearce, 1974). During the winter, when lice populations thrive, the numbers on a sheep can increase from 400 to 4000 by the spring. In the UK, the majority of cases occur between January and April, although infested sheep have been recorded in the UK as late as June (midsummer) (Bates, 2000d).

Shearing (generally carried out in the spring) can directly remove 36–66% of active lice and subject the remainder to a more variable microclimate (Murray, 1968; Heath *et al.*, 1995b). Solar radiation can cause temperatures at the tip of the fleece to rise as high as 75°C and skin temperature to 50°C within 10 min of exposure (Murray, 1968). At temperatures above 39°C *B. ovis* lays fewer eggs and at 45°C oviposition ceases completely (Murray, 1960). In recently shorn sheep high levels of solar radiation are a direct cause of mortality (Murray, 1968). In cooler climates the cumulative effects of repeated reversals of temperature gradients in the fleece as sheep move from sun to shade may be sufficient to prevent an increase in louse numbers (Murray, 1968).

Summer thunderstorms can also substantially reduce louse populations (Murray, 1960, 1963). Adults and nymphs of *B. ovis* can drown and eggs fail to hatch after saturation by heavy rain for more than 6 h. Similarly, dipping infested sheep in pure water can reduce lice populations by 26–35% and, when combined with shearing, reductions of 95.3–99.6% were recorded 48–52 days after treatment (Heath *et al.*, 1995b). However, the seasonal cycle of *B. ovis* can occur in the absence of these factors. Population decline begins when the daily mean and maximum temperatures are 11.5°C and 15°C, respectively (James *et al.*, 1998), and louse mortality caused by external factors such as excessively hot or wet weather, or by management practices (e.g. shearing), can be reflected in louse populations for 6 months or more (Murray, 1963). Heavy rain that results in saturated fleeces in the autumn can also reduce louse populations and limit the subsequent winter infestation (Kettle and Lukies, 1982).

Louse populations can increase through the summer as well if sheep are not shorn (Wilkinson *et al.*, 1982; Niven and Pritchard, 1985). Thus, *B. ovis* can survive the summer on 'carrier' sheep, and louse populations (sometimes heavy) can therefore be maintained throughout the year. Chewing lice have a low intrinsic rate of increase and spread slowly among sheep (Murray and Gordon, 1969; Cleland *et al.*, 1989). Furthermore, it is unlikely that an infestation will be detected until the population growth reaches the rapid increase phase, about 5 months after shearing (James and Moon, 1999). It also takes 5–6 months for newly infested sheep to develop noticeable symptoms.

The seasonal variation in louse populations appears to reverse in the case of the angora chewing louse (*B. limbata*). Adult *B. limbata* have been recorded to be most numerous in south-western Free State Province (South Africa) in the summer (from November to May), with the lowest numbers occurring during the winter (August). The largest proportion of adult *B. limbata* was found on the ventral surface during the winter, when populations were at their lowest (Brown *et al.*, 2005).

Survivability off the Host and Transmission

The majority of lice are contracted by direct animal-to-animal contact, particularly when animals are closely penned together (horizontal transmission) or through close contact between mother and offspring (vertical transmission). Lambs can be infested with the foot louse (*L. pedalis*) within 48 h of birth and goat kids can be infested with *B. limbata* within 2 days of birth (Fivaz *et al.*, 1990). In fleeces where the temperature ranges from 38°C at the skin surface to 15°C near the tip of the fleece, 69% of the mobile population (nymphs and adults) are within 6 mm of the skin surface and only 15% are more than 12 mm from the skin. When the tip of the fleece is shaded and warmed, adults and third-stage nymphs can come to the surface. It is under these conditions that *B. ovis* spreads within a closely herded flock. So lice spread quickly within flocks in hot climates (e.g. Australia) and relatively slowly in more temperate climates (e.g. the UK).

Transmission of the sheep chewing louse (*B. ovis*) from ewe to lamb depends on the product used for treatment. It can take 2–18 weeks after some treatments for all lice to die. If lambs are born during this period they can become infested and later reinfest the ewes when chemical treatment is no longer effective (Joshua, 2001). Similarly, uninfested 'clean' sheep can be infested if they are mixed with treated sheep before all the lice are dead (Joshua, 2001). Being permanent ectoparasites, lice are only accidentally detached from their host. Their low powers of survival off the host and their high temperature threshold for activity limit the probability of detached lice actively finding a new host. Thus lice are poorly equipped for seeking another host and contracting lice from the environment is limited. Studies in Australia have demonstrated that most *B. ovis* drop off infested wool staples attached to a fence within 1 h, with only 2/225 (0.9%) remaining after 24 h. Recent laboratory studies have shown that adults and nymphs of *B. ovis* can survive off the host for 11.7 and 24.1 days, respectively. If provided with raw wool they can survive longer (29 days for nymphs). In shearing sheds in winter and early spring, *B. ovis* adults and nymphs can survive for 14 and 16 days, respectively (Morcombe *et al.*, 1994). Individuals of *B. ovis* held away from their food source for extended periods are viable and able to reproduce, and nymphs can continue with their development. Adults and nymphs of *B. ovis* can survive on shearers' moccasins for up to 10 days; consequently, in Australia it is advised to microwave moccasins for 5 min to kill the potentially infestive lice. Lice can also be spread between pet goats and sheep through shared combs and brushes.

Feeding

It was once assumed that *B. ovis* fed on skin debris and wool fibres. Lipid-covered stratum corneum squama have been identified in the gut (crop, mid-gut and rectum) and faeces of *B. ovis*. However, nucleated keratinocytes from the inner epidermal strata were not observed, neither were wool fibres (Sinclair *et al.*, 1989). Vertical frozen sheep skin sections, with feeding *B. ovis* cryofixed *in situ* by liquid nitrogen, demonstrated *B. ovis* mandibles engaged in the outer stratum corneum (Sinclair *et al.*, 1989). Lipase activity has been demonstrated in the mid-gut, so sebaceous secretions may form an important component of the diet of *B. ovis* (Sinclair *et al.*, 1989). The evidence, then, indicates that *B. ovis* does not ingest wool fibres but feeds on loose scurf (epithelial debris, wax, suint) adhering to the wool fibres above the skin as well as loose (outer) stratum corneum (Sinclair, 1983). It has also been demonstrated that bacteria are an important part of the diet of *B. ovis* (Murray and Edwards, 1987).

Host Susceptibility

Not all sheep are susceptible to lice. James *et al.* (1998) observed that one-third of ewes failed to contract lice, despite being challenged five times and penned with

infested sheep. Pregnancy or lactation appeared not to have an effect on louse densities (James *et al.*, 1998). Transfer of lice is more rapid when the fleece is short (Murray, 1968). Lambs with shorter fleeces than ewes are, therefore, more susceptible, with louse burdens three times higher than those of ewes (James *et al.*, 1998). Sheep with a greater resistance to gastrointestinal parasites (e.g. *Trichostrongylus* spp.) appear to be less susceptible to *B. ovis*. Whether this effect is due to interaction of the effects of the parasites or to a correlation in underlying resistance mechanisms requires clarification (James *et al.*, 2002). Within the Anoplura, adaptation to the woolless areas of the sheep limbs allows *L. pedalis* to survive low environmental temperatures twice as long as *L. ovillus*.

The prevalence of *B. ovis* within flocks varies. In the UK, the majority of sheep (42.3%) carry light infestations, with medium or heavy infestations accounting for 22.0% and 16.7% of sheep, respectively (Bates, 2000d); significant numbers of sheep (19.1%) appeared to be uninfested, despite light to heavy infestations on contact sheep within the flock. Differences in *B. ovis* density do not necessarily reflect differences in individual sheep susceptibility. *B. ovis* spreads slowly through a flock and has a relatively slow intrinsic rate of increase (Murray and Gordon, 1969). Cleland *et al.* (1989) introduced two louse-infested sheep into a group of 50 louse-naive sheep and recorded that it took 69 days for live *B. ovis* to be recorded on all contact sheep.

Bates (2000d) showed that lambs appear to be more susceptible than ewes, carrying high parasite populations. Similar observations were made by James *et al.* (1998), in which lice on lambs reached densities more than three times those on the ewes, even though the lambs were infested for a much shorter time period, again suggesting that the lambs were more susceptible.

The severity of infestation also appears to depend on the breed, fleece length and overall health of the host, together with the ambient climate. Australian merinos can carry heavy infestations of *B. ovis* resulting in severe irritation, whereas sheep breeds in the UK appear to carry lower populations of lice with relatively little or no irritation. Studies by Niven and Pritchard (1985) indicated that fleece length can influence louse population growth, and Bates (2000d) observed that densities of *B. ovis* in the UK increased in relation to fleece staple length, with high populations observed on sheep with long fleece (Fig. 4.3).

Pathogenicity

Heavy infestations of lice are associated with animals in poor health and/or maintained in unhygienic conditions. James *et al.* (1998) observed that the most prolific source of lice on a particular property was a

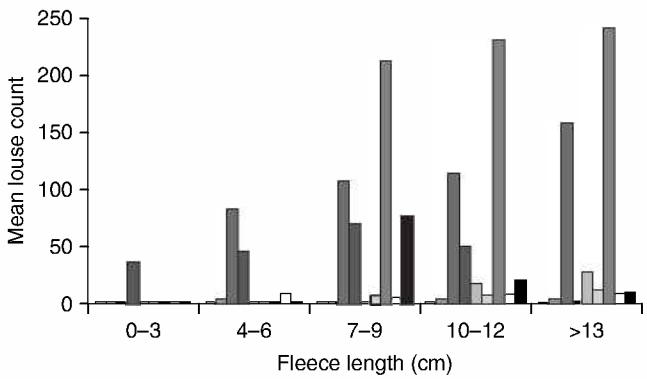

Fig. 4.3. The effect of fleece length on the numbers of *Bovicola ovis* infesting sheep in nine infested flocks within England and Wales (Bates, 2000d).

crippled, bottle-fed lamb and a group of ewes diagnosed with ovine progressive pneumonia. There is a correlation between sheep body condition score and the density of *B. ovis*: the lower the body condition score the higher the population of lice (Fig. 4.4) (Bates, 2000d). It is not certain whether louse infestations bring down the condition of the animal or whether the lice exploit an animal already out of condition as a result of concomitant infections or bad husbandry. Kettle and Lukies (1982) provided evidence to support the latter, in that no significant differences were observed between the body weights (lamb percentages and lamb weights at weaning) between louse-infested sheep and louse-free sheep over 4 year period.

It seems likely that lice exploit an animal already out of condition owing either to concomitant infections or bad husbandry. Scott (1952) observed that populations of *B. ovis* increased during winter in sheep on a low plane of nutrition, and Bates (2000d) observed that *B. ovis* populations were greatest on sheep with low body condition scores (Fig. 4.4). Concomitant infections/infestations that bring the body condition down may increase an individual sheep's susceptibility to lice. Anecdotal observations in the UK have shown a possible relationship between liver fluke (*Fasciola hepatica*) infection and high louse counts (Bates, 2000d). The presence of chewing lice could therefore be a significant indicator of underlying welfare problems within a flock.

Lesion (crust) formation in louse-infested sheep could be the result of trauma through mandibular attack on the outer stratum corneum by feeding lice (Sinclair, 1989), or of the involvement of skin bacteria associated with louse feeding (Murray and Edwards, 1988). The histological structure of the epidermis of heavily louse-infested Australian merinos has been shown to be substantially different from that observed in louse-free sheep (Britt *et al.*, 1985); however, in sheep carrying moderate louse burdens and, to a greater degree, in those carrying light infestations, portions of the epidermis more closely resembled the structure of louse-free merinos. The stratum corneum of louse-infested sheep was observed to be thicker than the very thin epidermis (<2μm) observed in normal skin, with the thickness of the uncornified epidermis and the stratum corneum significantly greater ($P<0.005$) than equivalent regions in louse-free merinos (Britt *et al.*, 1986).

Britt *et al.* (1986) identified three possible mechanisms by which *B. ovis* could cause epidermal thickening: (i) mechanical – due to the feeding (chewing) of *B. ovis*; (ii) mechanical – but due to self-inflicted trauma by the infested host; or (iii) immunological – through reaction to louse antigen in saliva and/or faeces. *B. ovis*

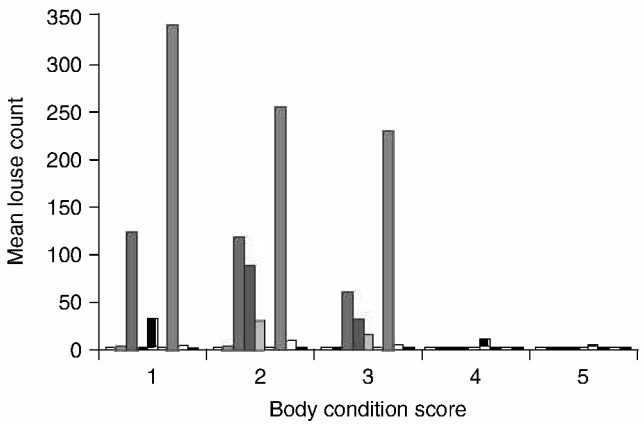

Fig. 4.4. The effect of body condition score on the numbers of *Bovicola ovis* infesting sheep (Bates, 2000d).

does not penetrate deeper than the outer layer of the stratum corneum (Sinclair *et al.*, 1989), so is less likely to be subject to immune effects of its host than are haematophagous or tissue-feeding arthropods (James *et al.*, 1998). Any immunological sensitivity elicited is more likely mediated by louse saliva (Sinclair, 1976), as intradermal injection of *B. ovis* faeces does not elicit a demonstrable response (Sinclair *et al.*, 1989).

Host Breed Differences

James *et al.* (1998) observed that densities of *B. ovis* on Polypay ewes were approximately ten times higher than densities found on Columbia ewes.

Clinical Signs

The chewing louse of sheep (*B. ovis*) favours areas close to the skin, especially on the withers, sides and flanks. Infestations of lice constitute a chronic dermatitis, with the skin and fleece usually exhibiting excessive scurf and the sheep showing symptoms of skin irritation, such as rubbing, biting and scratching (Britt *et al.*, 1986). As a consequence, the fleece becomes matted and impregnated with foreign material (Sinclair, 1976) (Fig. 4.5). Infected sheep have a ragged appearance, often with tags of wool hanging from the fleece (Fig. 4.6). Lousy wool is often yellow owing to a heavy suint and skin secretion, and shearers claim that it has a distinctive smell (Joshua, 2001). Newly infested sheep are very sensitive to lice; others, with established infestations, can develop quite severe infestations but show few signs (Joshua, 2001).

Particularly in the winter, when infestations are heaviest, the sucking louse *L. africanus* is found in large numbers on the loins, back, ribs and shoulders, and populations may reach several thousand. On goats, the distribution is different, with lice occurring on the upper neck, base of the ears, poll and ventral surfaces of the jaws (Durden and Lloyd, 2009). *L. africanus* parasitizing sheep and goats can cause serious losses of wool or mohair, even when present in relatively small numbers. Biting and rubbing damages the skin, wool and mohair. The fleece becomes pulled and ragged with broken fibres and may slip from or be pulled from the skin, creating bare areas that become contaminated with lice, lice exuviae, ova and faeces (Durden and Lloyd, 2009). *L. africanus* can stain the wool with blood, presumably as a result of undigested blood in its faeces. This wool will not scour. In heavily infested sheep, staining can extend from the withers to the rump and down the flanks (Durden and Lloyd, 2009).

Fig. 4.5. Merino sheep in Australia presenting with clinical signs of *Bovicola ovis* infestation (Photo © P. Bates).

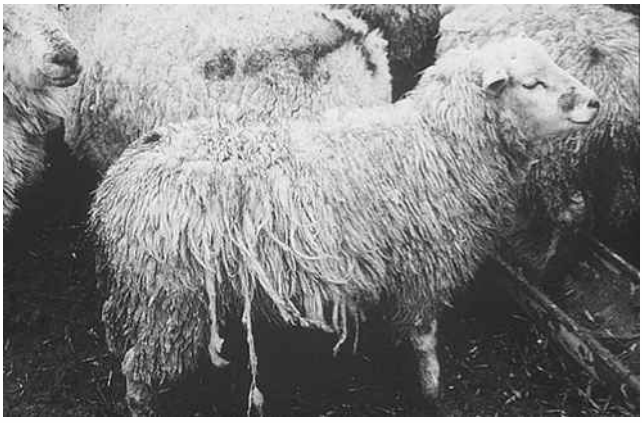

Fig. 4.6. Welsh Mountain sheep in the UK presenting with clinical signs of *Bovicola ovis* infestation (Photo © P. Bates).

The foot louse of sheep (*L. pedalis*) inhabits the haired skin between the hooves and knees and hocks, usually forming stationary clusters (often reaching several hundred insects per square centimetre). Heavy infestations may spread on to the woolled areas of the abdomen and scrotum. Heavy infestations of *L. pedalis* can cause foot stamping and biting and can be a cause of lameness.

Population Densities of *Bovicola ovis*

Population densities of *B. ovis* can vary with time. A few lousy sheep within a flock or mob will not cause widespread, noticeable lousiness, even after a few months. With shearing and incomplete chemical control, a new infestation may even take years to be noticed, although beyond a certain point of infestation uncontrolled louse populations can multiply rapidly. Louse numbers are often lowest in the 30–60 days following shearing.

Autumn is the most favourable time for lice populations to develop, when the immunity of the sheep is reduced by decreased feeding, seasonal effects, higher stocking densities and favourable environment (reduced solar radiation, relative humidity, temperature), and the wool length is optimal. Murray (1963) demonstrated that the size of a louse population can be related to louse mortality caused by thunderstorms 6 months earlier.

Populations of *B. ovis* show marked differences in rates of growth depending on the initial population size, spread among sheep and louse development on individual sheep. Differences among sheep in louse densities can be the result of variations in the size of the initial challenge, differences in the survival of lice after shearing or treatment and (though not necessarily) individual sheep susceptibility (James *et al.*, 1998). The smaller numbers of nymphs found in populations as they decline suggests that decline is due to reduction in fecundity of females, the hatch rate of eggs or the survival of early instars, rather than to death or emigration of adults (James *et al.*, 1998).

When a sheep has developed a light infestation (approximately one louse per 10 cm of fleece) there are already about 2000 lice present on the sheep (James and Moon, 1999). It will take 2–3 months for clinical signs (severe wool derangement) to occur, and longer if residual insecticide is present in the fleece or if the sheep are shorn (Joshua, 2001).

Monitoring Sheep for Lice

Regular monitoring for lice – and early detection when infestation begins – are key

to any well-planned control programme (see Chapter 7). In Australia, flock owners have been given a simple method for monitoring for lice. Select at least ten sheep and examine each sheep by parting approximately 10 cm of wool to skin level, make at least ten partings per side of the sheep and calculate the numbers of lice. If no lice are seen, examine another ten sheep or reinspect the flock in 3–4 weeks. If you need glasses to read, then you will need them to see lice *in situ*. Distribution of lice is uneven and can be found in high numbers in localized colonies and can be missed if the fleece is only parted in one or two places. If 10% of a flock is infested, selection of only one sheep at random will give only a one-in-ten chance of selecting an infested sheep.

Early in infestation only a few sheep will be infested. Visual inspection is not always reliable if sheep are louse free. Lice in small numbers are difficult to find – at least 400–500 lice must be present before an infestation can be detected by inspection on unshorn sheep (Joshua, 2001). If a sheep has 100 lice, equivalent to 0.5 lice per parting, inspection over 20 partings will only give a 60% chance of finding lice on this animal. In light infestations on sheep with less than 6 months of wool growth, lousy sheep may be impossible to identify and lice difficult to find. Medium-to-heavy infestations are easier to detect.

Lice increase at a greater rate on sheep that have a low immune system, are in poor condition or are affected by disease. These can be targeted when inspecting for the presence of lice in a flock (Joshua, 2001); sheep presenting with signs of wool derangement and poor condition should be targeted. Animals can start rubbing with as little as 100 lice, so selecting a rubbing sheep greatly improves the chances of finding an infested animal. Inspections can be carried out at any time that sheep are gathered, especially at crutching or shearing. In merinos, it is necessary to pay particular attention to neck folds and longer wool on the neck. In woolly sheep, lice can be found anywhere along the sides, neck, back or rump (Joshua, 2001). It is important to record findings so that subsequent inspections can be compared.

Diagnosis of Pediculosis

There has been an increase in the prevalence of *B. ovis* in England and Wales since lifting compulsory dipping for the sheep scab mite (*Psoroptes ovis*) in 1992. The clinical signs of chewing lice can be confused with those of sheep scab and so possible resistance may occur in both ectoparasites if they are not professionally identified and the correct treatment applied. Sheep can also present with mixed infestations of sheep scab and chewing lice, although pre-existing infestations of lice make it difficult for scab mites to colonize. Lice can colonize sheep with pre-existing scab with relative ease.

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Flies (Diptera)

The true flies (Diptera) are described by Richards and Davies (1977) as having, in the adult form, a single pair of membranous wings, with the hind pair modified into haltares. They generally have sucking mouthparts, usually forming a proboscis and sometimes adapted for piercing. The labium is usually expanded into a pair of fleshy lobes. The prothorax and metathorax are small and fused with the large mesothorax. The tarsi are generally five segmented. Metamorphosis is complete, with egg, larva, pupa and adult stages.

Flies can be parasitic as adults either through blood feeding (haematophagous) or through feeding on body secretions (secretophagous) – commonly known as 'nuisance' flies. They can also be parasitic in the larval form through feeding on living tissue (myiasis).

Blood-Sucking Flies

Although all blood-sucking fly species, including tsetse flies (*Glossina* spp.), horn-flies (*Haematobia* spp.), stable flies (*Stomoxys* spp.), horseflies (*Tabanus* spp., *Hybromitra* spp., *Haematopota* spp., *Chrysops* spp.) and blackflies (*Simulium* spp.) readily feed off sheep and goats, only the sheep ked (*Melophagus ovinus*) and the biting midges (*Culicoides* spp.) are regarded as economically important. *M. ovinus* can be the cause of anaemia and leather damage and *Culicoides* spp. are vectors of a number of important viral diseases of sheep and goats, including bluetongue virus (BTV).

Hippoboscidae

*Sheep keds (*Melophagus ovinus*)*

Sheep keds (*M. ovinus*) belong to the dipteran family Hippoboscidae. The Hippoboscidae are permanent, obligate, blood-feeding ectoparasites of mammals and birds (Fig. 5.1).

Adult *M. ovinus* are wingless red/brown insects, 4–6 mm in length, with a broad head and stout piercing mouthparts. Keds are ectoparasites of sheep in temperate countries and in the cooler highlands of the tropics, but are absent from the hot, humid tropics.

LIFE CYCLE. *M. ovinus* are permanent ectoparasites, spending their entire life cycle on the sheep. The Hipposcidae are closely related to the blood-sucking Glossinidae (tsetse flies), in that the female is viviparous, retaining the larva internally until it is fully grown and depositing it as an immobile

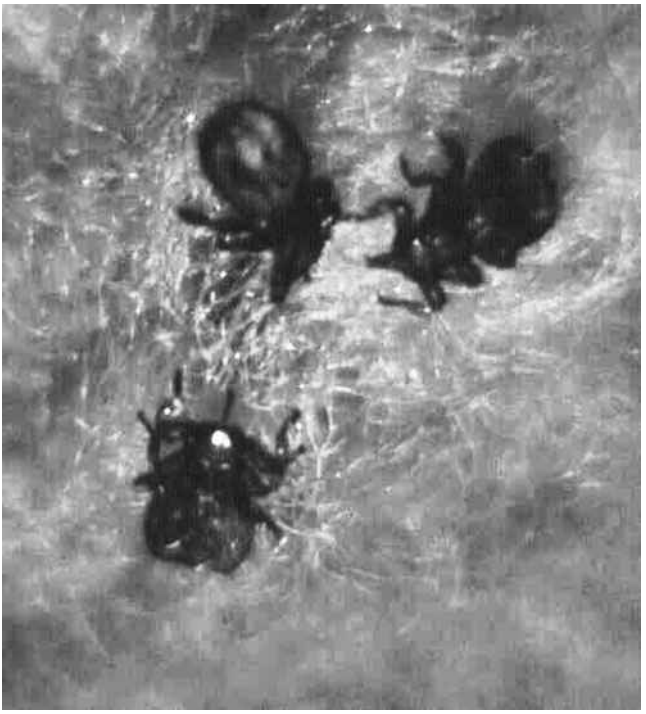

Fig. 5.1. Adult sheep keds (*Melophagus ovinus*) (Photo © Youngs Animal Health).

prepupa which pupates once it is attached to the wool (Hutson, 1984). Pupae are deposited when the female is 13–14 days old, with subsequent larvae deposited every 7–8 days. In its lifetime of 4–5 months a female will produce about 15 larvae, a comparatively slow rate of increase for a parasitic insect. Deposited larvae pupate within 6 h and the duration within the pupal stage is 20–26 h. Thus, a cycle from newly emerged adult female to emergence of an adult of the next generation is 5 weeks. Pupae develop over a relatively narrow range of temperature (25–34°C), with optimal development at 30°C. Puparia are glued to the fleece and carried away from the skin as the fleece grows. Temperature at skin level will be close to 37°C, but is considerably cooler nearer the fleece tip. Puparia are therefore deposited in areas where a suitable temperature will be found during the 3 weeks of pupal development. Mating takes place on the host and sperm can be stored by the female and remain viable for a series of pregnancies (Hutson, 1984).

HOST SPECIFICITY. *M. ovinus* is restricted to a single host, the domestic sheep (Hutson, 1984).

SEASONALITY. Peak *M. ovinus* densities on lambs are reached in winter but these decline over summer as a result of shearing and increased temperatures (Olaechea *et al.*, 2007a). Seasonality may also be due to cycles in development and declines in immunity (Nelson, 1962).

SURVIVABILITY OFF HOST. *M. ovinus* cannot survive long off the host. At temperatures between 15 and 27°C some 99% of *M. ovinus* are dead after 7–8 days and 100% are dead after 9 days (Olaechea *et al.*, 2007b), although high humidity and cool temperatures can extend this period to 24 days (Graham and Taylor, 1941).

TRANSMISSION. Unlike other hippoboscid flies, *M. ovinus* is wingless throughout its life cycle and can only transfer during direct contact between sheep. This is an active process, concentrating on pregnant ewes before lambing and, later, on well-fleeced lambs (Hutson, 1984).

FEEDING AND PATHOGENICITY. Adult keds are blood feeding and large numbers can gradually exsanguinate the host and cause variable degrees of anaemia. *M. ovinus* feeds at approximately 36 h intervals and a full feed may take 5–30 min; mature *M. ovinus* can imbibe a blood meal equivalent to over 90% of its own weight (Hutson, 1984).

CLINICAL SIGNS. In hoggs (yearling sheep), over 50% of the pupae are found in the neck region, while 60% of *M. ovinus* adults are found on the forelegs and flanks. On lambs, puparia are concentrated on the hind legs, neck and belly, although substantial numbers of adults are found on the flanks and forelegs.

VECTORS OF DISEASE. *M. ovinus* is a vector of the trypanosome *Trypanosoma melophagium*, with which sheep becoming infected by crushing infected keds in their mouths. *T. melophagium* is not pathogenic to sheep, but may be harmful to the ked (Hutson, 1984). *M. ovinus* is also capable of transmitting BTV between sheep (Luedke *et al.*, 1965). Transmission is mechanical. However, as *M. ovinus* feeds regularly every 36 h, biological transmission remains a possibility.

Ceratopogonidae

Biting midges belonging to the family Ceratopogonidae (*Culicoides* spp.) are regarded as important, particularly as vectors of BTV and other viral diseases and in causing reduced productivity through continual 'nuisance' through their biting. To a lesser degree, they can also be responsible for a form of allergic dermatitis in sheep.

*Biting midges (*Culicoides *spp.)*

Adult *Culicoides* spp. are small (1–4 mm in length) and are found from the tropics to the tundra regions and from sea level to an altitude of 4000 m. By their very abundance, *Culicoides* spp. have a very detrimental effect owing to the nuisance caused by the bites from the female. Their presence can thus hinder the economic growth of certain areas by blocking agricultural activities and the development of tourism (Thiry *et al.*, 2006).

The rapid spread that followed the initial outbreak of BTV-8 in northern Europe in 2006 is considered a consequence of climate changes. These changes have allowed the northern European midge species such as *Culicoides obsoletus* to become effective vectors of BTV-8. *C. obsoletus* is a very small fly, no bigger than 1 mm in length, and it is the most abundant of the *Culicoides* spp. in northern Europe.

LIFE CYCLE. In most species of *Culicoides* the life cycle is poorly understood. Adults usually live for about 20–90 days, depending on ambient conditions. The adult lifespan of *C. obsoletus* is 3.5 months, considerably longer than that of most other *Culicoides* spp. Thus, BTV has a longer time to replicate in the female midge; this longer lifespan allows more bites to occur and so more animals can be infected.

Mating takes place in swarms. After blood meals to develop their ovaries, females lay between 100 and 200 eggs in areas of specific humidity and abundant organic material (e.g. the liquid edges of manure heaps, manure-polluted watercourses, mud, water meadows, etc.). Larval development is optimal in these semi-aquatic microhabitats. In general, larvae are mainly found in the first 5–6 cm of the upper level of the medium concerned. Midge larvae can feed on organic matter, or are predatory on nematodes, bacteria and protozoa, or can be cannibalistic. Pupae are also found on the surface of the medium where the larval development takes place. During the summer, the development from egg to adult takes a couple of weeks but it can take up to 7 months during the overwintering period.

DISPERSAL. *C. obsoletus* breeds close to sheep and cattle sheds, and rarely actively moves away from the site where it emerged from the pupae (Mellor *et al.*, 2000). There is some evidence that the midges may actually breed in livestock buildings – thereby causing a year-long problem. Their active dispersal is therefore limited (Mellor *et al.*, 2000); passive dispersal by warm humid winds blowing at low altitude (below 2000 m) at a mean speed of 10–40 km/h is a far more important factor, and the midges can be carried over a distance of several hundred kilometres by this means (Braverman and Chechik, 1996).

FEEDING. *Culicoides* will feed on all warm-blooded vertebrates (including humans), but prefer domestic livestock. Sheep and goats are generally bitten along the sides of the belly and lower legs. Only adult female *Culicoides* blood feed as they require the blood protein to develop their ovaries. Male *Culicoides* are generally flower dwelling, and feed on nectar, sugar and pollen, as well as liquids from decomposing organic matter (Chaker, 1981). *Culicoides* spp. tend to be active around the afternoon period, at sunset/sunrise and during the night, preferring still warm conditions. However, some species (e.g. *Culicoides nubeculosus*) bite preferentially in full daylight. Females suck blood every 3–5 days, and during their lifespan can feed more than three times.

SEASONALITY. The survival, activity and dispersal of *Culicoides* spp. are strongly influenced by meteorological factors such as temperature, humidity and wind speed. Temperature is the main environmental factor, with activity highest between 13 and 35°C (Braverman and Chechik, 1996). Losson *et al.* (2007) observed *C. obsoletus* flight activity at temperatures ranging between 6 and 12°C in cattle sheds during the winter of 2006–2007 in Belgium. Larvae are particularly sensitive to desiccation, and rain prevents adults taking flight. Adults of *C. obsoletus* and *Culicoides scoticus* are on the wing from March until late December, and those of *Culicoides impunctatus* from late May to late September. In general, two generations of *Culicoides* are produced each year, a large one in the spring and a smaller one in the summer (Rieb, 1982). Some larvae and pupae overwinter in protected breeding places and continue development in warmer weather.

BLUETONGUE. Bluetongue is an infectious but non-contagious viral disease of a broad spectrum of domestic and wild ruminants. It is a notifiable disease listed by the World Organisation for Animal Health (OIE). The causal virus (BTV) belongs to the *Orbivirus* genus of the family *Reoviridae* and is transmitted by midges of the genus *Culicoides*. Sheep are the main host, but infection also occurs, usually subclinically, in free-living ruminants, cattle and goats. Severe disease in sheep involves fever, inflammation of the mucus membranes of the oral cavity and nasal passages, enteritis and lameness. Local breeds of sheep are usually more resistant than others to infection (Thiry *et al.*, 2006). The infection is usually inapparent in goats and cattle, but these can then act as a reservoir for the virus. However, some serotypes (e.g. serotype 8 – BTV-8), which recently caused infection in northern Europe, exhibit greater virulence in cattle than in the past (Thiry *et al.*, 2006).

BTV was originally enzootic in Africa, but in the last 65 years has become widely distributed throughout the world. Outbreaks of BTV have occurred in Africa, the Middle East, Pakistan, India, Japan and the USA. In Australia, Brazil, Canada and the West Indies, BTV is present but no clinical disease has been reported (Kettle, 1995). Before 1998, BTV was considered exotic in Europe, with just a few sporadic outbreaks (e.g. in Spain and Portugal from 1956 to 1960) (Saegerman *et al.*, 2008). Since 1999, there have been widespread outbreaks of BTV in Greece, Italy, Corsica (France) and the Balearic Islands (Spain). Cases have also occurred in Bulgaria, Croatia, Macedonia, Kosovo and the former Yugoslavia. BTV serotypes 2, 4, 9 and 16 were involved and it was postulated that the virus had spread from both Turkey and North Africa.

Until 2006, the geographical distribution of BTV extended between 50° N and 35° S.

BTV was discovered in northern Europe for the first time in 2006. Initially, Germany, Belgium and the Netherlands and, to a lesser extent, Luxembourg and France were affected. In 2007, northern Europe experienced a dramatic increase in new cases in all existing infected areas, and cases numbered into the many tens of thousands as disease steadily spread across Europe. Affected countries witnessed increased mortality rates in animals and production losses, which caused severe economic hardship for the farming industry. During this recent unexpected emergence in northern Europe the causal agent, BTV-8, mainly infected sheep and cattle. What was striking was the fact that BTV was able to spread all over northern Europe, including the UK, in less than 2 years.

Competent vectors of BT include *Culicoides imicola* in Africa and Mediterranean Europe, *Culicoides sonorensis* in North America, *Culicoides insignis* and *Culicoides pusillus* in South America, and *Culicoides brevitarsis* in Australia. In Europe, *C. obsoletus* and *C. scoticus* have been identified in central Italy, and *Culicoides pulicaris* in Sicily. *Culicoides dewulfi* is recognized as a vector in northern Europe. BTV persists in *Culicoides* spp. during their lifespan. After a blood meal, the virus passes through the insect's intestinal wall and is distributed via the haemocoel to various tissues and then to the salivary glands, where it continues to replicate. It is subsequently excreted in the insect's saliva. Transmission is solely by insect bite. The vector reaches its maximum infective capacity 10 days after having absorbed blood from a viraemic animal.

Bluetongue disease occurs after the introduction of infected sheep or vectors to a virus-free area where a competent vector is indigenous. Subclinical infection occurs in goats (and cattle) and these species could serve as reservoirs of infection (Thiry *et al.*, 2008). When the disease is enzootic, clinical signs are mainly seen in susceptible imported sheep. The geographical distribution of BTV depends on the presence of a *Culicoides* vector and the disease is therefore seasonal and seen mainly in hot, humid areas, near stagnant pools of water. In temperate regions, the disease mainly occurs at the end of summer or the beginning of winter, whereas in tropical countries it mainly occurs in the spring or early summer, but may also occur throughout the year. In the absence of transovarial transmission of the virus in insects, other mechanisms have been suggested to explain the phenomenon of overwintering, i.e. virus survival over the winter period and during 9–12 months in the absence of adult vectors (Thiry *et al.*, 2006). Such a mechanism would be dependent on the establishment of chronic infections in sheep and cattle.

Nuisance Flies

Nuisance fly species feed on nasal/lachrymal secretions and on wounds initiated by their feeding activity or those caused by blood-feeding flies, ticks, etc. The most important species in northern Europe is the headfly (*Hydrotaea irritans*).

*The headfly (*Hydrotaea irritans*)*

The headfly (*H. irritans*) is a muscid fly, similar in size to a housefly, with an olive-green abdomen and orange-yellow wing bases (Fig. 5.2). The fly occurs throughout the UK, although headfly-related damage has been recorded only in the north of England and the Scottish borders.

LIFE CYCLE. *H. irritans* is univoltine, producing only one generation of adults a year. Eggs are laid in mid-to-late summer (July and September in the UK), in soil with a dense cover of vegetation, usually on the edge of (particularly coniferous) woodland. Eggs hatch within 7 days and the carnivorous larvae (that feed on other insect larvae) feed and grow until late autumn, when development ceases, only to resume again in the following spring. Maximum mortality occurs in the early larval stages (Anon., 1979). Pupation occurs in late spring (May), with adults emerging after a minimum of 4 weeks.

Fig. 5.2. Adult sheep head fly (*Hydrotea irritans*) (Photo © Crown Copyright 2011).

SEASONALITY. Time of emergence varies, but is correlated with temperature and can be predicted. Emergence follows the seasonal increase in air and soil temperature with a lag of 2 weeks between the rise in air temperature and peak fly numbers (Anon., 1979). In Northumberland, north-east England, emergence is spread over 6 weeks from the end of June to July. Emergent adults take 48 h to mature before seeking food. Flies are active only during the day and will not take to the wing in windy conditions. Adults and larvae are prone to desiccation and tree cover offers protection from the sun, with flies venturing out for short distances to feed. In wet/windy weather, adult flies rest on trees, attacking sheep in massive numbers when conditions improve. Population densities range between from five to 200,000 flies/ha (Anon., 1979). Dispersal of adults is rapid and over considerable distances at rates of 500 m/day, giving ample opportunity to spread infectious diseases (Anon., 1979). As there is population interchange of flies from different parts of a woodland, any areas that are cleared will be quickly repopulated (Anon., 1979).

HOST SPECIFICITY. The main host of *H. irritans* is sheep, in which it feeds from lachrymal and nasal secretions and the base of the horns (see below), but it will also feed from the eye secretions of cattle.

FEEDING AND PATHOGENICITY. Adult flies take a blood meal every 10 days and feed on honeydew and carrion as a source of protein between blood feeds (Anon, 1979).

Horned sheep with hairy faces (e.g. Scottish Blackface, Swaledale, etc.) are most susceptible. Flies rasp away at the base of the horn but also on nasal and lachrymal secretions using the prestomal teeth on the end of the proboscis. Trauma may produce breaks in the skin resulting in the exudation of blood and serum, which attracts more flies. Continual feeding at the periphery of the lesion can lead to possible loss of large areas of skin from the head ('broken head' or 'black cap') (Fig. 5.3). In severely affected flocks, 50% of ewes and 90% of lambs can present with lesions. Secondary infections and, on occasions, blowfly strike may occur. However, wounds usually heal following the cessation of fly activity. Lesions at the skin/horn junction of young sheep and wounds resulting from fighting in rams also attract headflies. Headfly damage can also be aggravated by faulty shearing and other accidental wounds (Anon., 1979).

CLINICAL SIGNS. Swarms of flies initiate head shaking and rubbing of the head against the ground or undergrowth or scratching with the hind feet.

PREVENTION. To avoid headfly, sheep should be kept over 1 km from any woodland – especially in July and early August. This is generally impracticable as the term 'woodland' refers to areas with trees over 1 m in height (Anon., 1979). The breeding of polled Scottish Blackface lambs using Derbyshire Gritstone rams is very slow and the small horns of some crossbreeds are more susceptible to injury than normal Blackface horns (Anon., 1979).

Fig. 5.3. Head lesion ('black cap') caused as a result of feeding by the sheep headfly (*Hydrotaea irritans*). (Photo © Crown Copyright 2011).

Myiasis

Myiasis is the infestation of living tissues with the larvae of true flies (the Diptera). From an entomological viewpoint, flies associated with myiasis can be divided into three groups.

1. Accidental – e.g. through the consumption of eggs or larvae of *Musca domestica* or *Sarcophaga* spp. with contaminated food, which then survive in the alimentary canal.
2. Obligatory – where parasitism is essential for the survival of the species, for example, nasal botflies (*Oestrus ovis*), screw-worm flies (e.g. *Chrysomya bezziana*) and goat warbles (*Przhevalskiana* spp.).
3. Facultative – species that can survive without the need to be parasitic, generally through feeding off carrion. Cutaneous myiasis ('blowfly strike' or 'maggot fly') caused by larvae of the families Calliphoridae, Sarcophagidae or Chrysomyinae constitutes a major disease problem throughout the world. These types of fly can be divided into primary flies (e.g. *Lucilia cuprina*) that initiate myiasis, secondary species (e.g. *Chrysomya rufifacies*) that are unable to initiate myiasis and tertiary species that are involved at a later stage when the host animal is almost dead.

Facultative myiasis

The majority of fly species responsible for facultative myiasis belong to the families Calliphoridae or Sarcophagidae.

The Calliphoridae is a large family of over 1000 metallic or testaceous fly species, divided into several subfamilies, of which the Chrysomyinae and the Calliphorinae are of particular medical/veterinary importance (Kettle, 1995). The Chrysomyinae contain the genera *Cochliomyia* and *Chrysomya*, which are found in the warmer regions of the world. *Cochliomyia* spp. are green to violet-green blowflies, while *Chrysomya* are green or greenish-black blowflies. Until recent transcontinental introductions, *Cochliomyia* spp. were restricted to the New World and *Chrysomya* to the Old World (Kettle, 1995). The Calliphorinae contain the worldwide genera *Lucilia* (= *Phaenicia*) – the 'greenbottles' and *Calliphora* – the 'bluebottles'. *Lucilia* spp. have a glossy green or coppery green thorax or abdomen and measure from 6 to 9 mm.

Calliphora spp. are larger flies (10–14 mm) with a black thorax, and have a steely blue to blue-back slightly metallic coloured abdomen.

The Sarcophagidae is a large family that is distributed worldwide, with over 2000 species of grey-black, non-metallic flies with prominent stripes on the scutum (Kettle, 1995). These are viviparous or ovoviviparous flies, depositing active first-instar (L_1) larvae or eggs that hatch immediately on deposition. Mature third-instar (L_3) sarcophagid larvae have posterior spiracles recessed in a posterior depression and so are hidden from view. The spiracles have three slits which are surrounded by an incomplete peritreme (Kettle, 1995). The family includes the genus *Wohlfahrtia* which has a grey abdomen with a pattern of black spots that are unaffected by the angle at which they are viewed. The abdomen of the genus *Sarcophaga* has a tessellated pattern or silver-grey and black markings, which vary with the angle of the incident light (Kettle, 1995). A number of species of *Sarcophaga* have been associated with myiasis in sheep or goats, usually as tertiary or accidental agents, but some species are facultative agents.

Sheep blowfly strike

FLY SPECIES RESPONSIBLE.

Calliphoridae. Lucilia. cuprina (the 'Australian sheep blowfly', body length 10 mm) is the major primary strike species found in Australia, New Zealand and South Africa. It is a copper-green colour with reddish eyes and 'smooth skinned' larvae. *L. cuprina* can breed in carcasses, particularly when prevented from breeding on sheep, thereby maintaining low-level populations (Wilson and Armstrong, 2005). In Australia 79% of sheep flocks in Queensland have been reported to be affected by *L. cuprina*, with 0.5% and 1.1% of animals struck (Ward, 2001). In New South Wales between 60% and 90% of flocks are reported to be affected, with 1–2% of animals struck (Wardhaugh and Dallwitz, 1984; Wardhaugh and Morton, 1990). *L. cuprina* was introduced to New Zealand from Australia in the late 1970s (Heath and Bishop, 1995).

Lucilia sericata (the 'greenbottle') is the primary strike species affecting sheep in northern Europe and is probably the commonest ectoparasite affecting sheep in the UK. Strike caused by *L. sericata* is indiscriminate; even sheep in the best-kept flocks can be affected and if measures are not used to prevent strike then between 3.7% and 5% of lambs could be struck between June and August (Bates and Rankin, 2002). In a postal survey of sheep farmers in England and Wales, 80% reported at least one case of strike in their flocks, with an estimated half a million sheep struck annually, and an average of 1.6% of sheep struck annually within flocks (French *et al.*, 1992). Blowfly strike appears to be more prevalent in southern England, with 90% of sheep farmers in south-east and south-west England reporting strike, and 2.8% of sheep struck. In the north of England, 60% of sheep farmers reported strike, with 0.7% sheep struck (French *et al.*, 1992). A recent postal survey in Britain showed that 75% of sheep farmers record strike in their flocks, with 1.4% of ewes and 2.8% of lambs affected (Bisdorff *et al.*, 2006). In the Netherlands, 52% of flocks recorded at least one case of strike, with 2.9% of sheep struck (Snoep *et al.*, 2002). *L. sericata* is also found in New Zealand and South Africa, where it is considered to be less significant than *L. cuprina*. *L. sericata* was the major primary strike species in New Zealand before the introduction of *L. cuprina* from Australia in the late 1970s (Heath and Bishop, 1995).

Calliphora vicina Robineau-Desvoidy (= *Calliphora erythrocephala* Meigen) (the 'bluebottle') is a large, blue, bristly fly. *C. vicina* is a common, widely distributed species which has followed man into South America, the Afrotropical Region (Mauritius and South Africa), northern India, Australia and New Zealand. In northern Europe, is a very common urban species that is closely associated with man (Smith, 1986). Adult flies are attracted to faeces, decaying meat and fruit. *C. vicina* is considered to be associated with secondary sheep blowfly strike, although anecdotal evidence suggests that the species may be the cause of primary

strike in the UK (north Wales), particularly towards the end of summer.

Calliphora stygia (the 'eastern golden-haired blowfly' or the 'brown blowfly' of Australia and New Zealand, body length 13 mm) prefers cooler conditions, and occurs in larger numbers in spring and autumn, but may be seen on sunny winter days. It disappears during the heat of summer. Although the species mainly breeds in carcasses, it can be troublesome in the Australian spring, especially in 'daggy' sheep and ewes with lambing stain. In New Zealand, *C. stygia* is a secondary strike species (Heath and Bishop, 1995).

Calliphora augur (the 'lesser brown blowfly') and *Calliphora dubia* (both 11 mm long) are almost identical, with a metallic blue shield on their abdomens, and have similar habits. *C. augur* occurs mostly in the Australian summer, laying live young capable of feeding immediately. *C. augur* breeds mostly in carcasses, but will oviposit into wounds, weeping eyes, etc. The closely related *C. dubia* occurs in the west of Australia but has now extended its range into New South Wales (Levot, 2009a).

Phormia terranovae (the 'black blowfly') generally breeds in carrion in the UK, but can be a facultative agent of myiasis (Kettle, 1995).

Chrysomyinae. Chrysomya. rufifacies (body length 9–10 mm) prefers to breed on carcasses, but can be a secondary fly striking sheep after *L. cuprina* has initiated a strike. The adult is metallic blue-green but can be distinguished from *L. cuprina* by the broad bands on its rounder abdomen and by its black front legs. The larvae or 'hairy maggots' appear dark and have sharp fleshy projections/spines over much of the body; they are 14 mm long when fully grown (Levot, 2009a). These maggots repel primary maggots and will actively feed on them in carcasses. By doing this, they help to control *L. cuprina* and so can be regarded as beneficial flies. However, on sheep they can cause extensive damage not only to the skin but also to the underlying tissues of the struck sheep. By the time these maggots reach full size on sheep the animal has been struck for more than a week – initially by *Lucilia* but then by *Chrysomya*. The very similar, but smaller, *Chrysomya varipes* fulfils a similar role (Levot, 2009a). *C. rufifacies* has been recorded in Australia (Levot, 2009a) and New Zealand (Heath and Bishop, 1995).

Chrysomya chloropyga can be an agent of primary and secondary sheep myiasis in South Africa. *Chrysomya albiceps* and *C. varipes* are related to *C. rufifacies* and also have 'hairy maggots'; they are also both frequently involved in secondary myiasis of sheep in Australia, New Zealand and South Africa. *Chrysomya megacephala* (the 'oriental latrine fly') is found in large numbers around latrines and is a nuisance in slaughterhouses and in open-air meat and fish markets; it may also be involved in wound myiasis. It has recently been imported to North Africa, having only been previously reported in South Africa (Zumpt, 1965).

TYPES OF BLOWFLY STRIKE. Blowfly strike can be classified as foot/wound strike, body strike or breech strike.

Foot/wound strike. Foot/wound strike requires predisposing (often necrotic) tissue damage, such as that seen in abscesses/foot rot, or open wounds such as dog bites or barbed wire lacerations. Different fly species have different requirements for attraction to a potential food source and for the stimulation of oviposition. Many species of bluebottle (*Calliphora* spp.) will only strike corpses or necrotic tissue, and some will only strike sheep when stimulated to do so by a previous larval infestation (i.e. they are secondary strike flies). Although foot strike is medicinally beneficial (with the maggots eating away the infected tissue), they will subsequently augment the natural population of blowflies in the immediate area. Foot/wound strike accounts for 11.4% of strikes in England and Wales (French *et al.*, 1995).

Body strike. Body strike (Fig. 5.4) is the most specific of all the strikes and probably the least understood. Flies are attracted to sheep by the odours of excessive 'sweating' and/or decaying organic matter in the fleece, usually over the loins, shoulders, flanks, neck, back, throat or abdomen. Individual animals may be repeatedly struck owing to the continual release of attractants encouraging

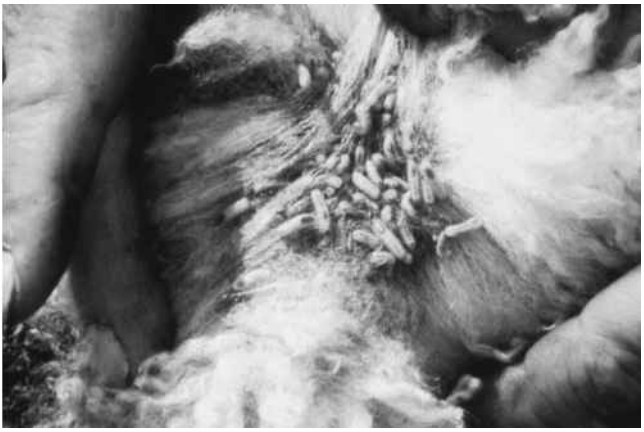

Fig. 5.4. Body strike (traumatic myiasis) caused by larvae of the greenbottle (*Lucilia sericata*) (Photo © Novartis).

the flies to single out a particular sheep for oviposition. Body strike accounts for 19.7% of strikes in England and Wales (French *et al.*, 1995). *Lucilia* spp. can also cause pizzle strike, when they are attracted by wet, urine stained wool.

Breech (tail) strike. In breech or tail strike (Fig. 5.5), flies are attracted to fleece contaminated with urine and/or faeces and are particularly attracted to scouring (possibly resulting from parasitic gastroenteritis, or PGE). Breech strike in sheep is the most indiscriminate of all strikes, with adult female flies attracted to faecal matter as a source of protein. If left untreated, the larvae may burrow into the animal and/or track up the anus/vagina, which is extremely difficult to detect. *L. cuprina* generally causes breech strike.

Lambs are significantly more susceptible to breech strike by *L. sericata* than are ewes (Bates and Rankin, 2002), which is explained by the fact that the overall degree of scouring (scored 1 to 5, where 1 = no scouring and 5 = excessive scouring) for lambs was greater than that for ewes. Although the prevalence of breech strike was higher in lambs with scores 2 and 3, it was noted that lambs with scores of 1 (i.e. no scouring) could also be struck in the breech. It was also noted that strike was not inevitable in animals with high scores, in that only a very small proportion of animals presenting with scores of 2 and above were actually struck. There may, then, be predisposing factors other than the presence of faeces and urine that attract gravid flies to the breech. A model for artificial breech strike has been investigated by Groves *et al.* (2000) in which scouring was initiated using a non-insecticidal laxative. However, the technique did not prove to be effective as L_1 larvae did not find the conditions favourable and failed to establish active breech strike lesions. This result was of interest though as conventional thinking would suggest that these conditions would have been ideal for larval colonization. The possibility exists that a large number of natural breech strikes (caused by *L. sericata*) may be initiated from a body lesion close to the breech (e.g. the tailhead) and that the larvae 'track down' to the breech as the infestation progresses, and the instars become hardier and develop more robust and mechanistic feeding mechanisms. This supposition is supported by the fact that in a Veterinary Laboratories Agency (VLA) field study egg batches were observed to be deposited on the soiled breech that did not appear to hatch (Bates, unpublished data).

Breech strike is the most common type of strike, accounting for approximately 71% of all strikes and 81% of lamb strikes in England and Wales (French *et al.*, 1995).

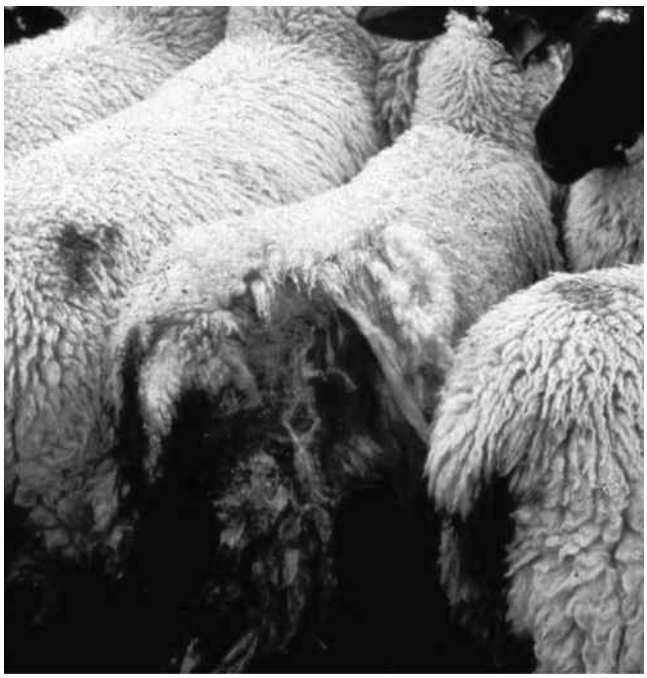

Fig. 5.5. Breech strike (traumatic myiasis) caused by larvae of the greenbottle (*Lucilia sericata*) (Photo © Novartis).

LIFE CYCLE OF *LUCILIA SERICATA* AND *LUCILIA CUPRINA*. Dipteran flies undergo complete metamorphosis, consisting of the egg, three larval stages, pupa and adult. The life cycle (egg to adult) of *L. cuprina* under optimal conditions (28°C) can be 11–12 days. In *L. sericata*, development from first (L_1) to the third (L_3) instar can take 5–11 days on a carcass but only 3 days on the back of a sheep – or even shorter in a wound.

The life cycle of *L. sericata* and *L. cuprina* infesting sheep can further be divided into nine phases, as shown in Table 5.1 and described below.

Table 5.1. The life cycle of *Lucilia* broken down into nine separate stages.

Adult fly	1	Emergence
	2	Feeding off host
↓	3	Reproduction
	4	Attraction
↓	5	Landing
	6	Oviposition
Eggs	7	Hatching
↓		
Larvae	8	Development
↓		
Pupae	9	Pupation

Phase 1: emergence. Under favourable temperature conditions, adult *L. cuprina* (Australian blowflies) emerge from the pupa case around sunrise 6–10 days after pupation (Levot, 2009a). Under summer conditions in the UK, adult *L. sericata* (greenbottles) emerge 2–4 weeks after pupation. Adult flies live for approximately 2–3 weeks. Blowflies have a low population density, with under 1500 flies present per square mile. Dispersal of adults is affected by habitat, and in favourable areas adults may disperse only a few kilometres from their point of emergence. This is supported by the existence of localized insecticide-resistant populations that spread slowly (Kettle, 1995).

Phase 2: feeding off the host. Adult blowflies of both sexes can exist on a sucrose-rich diet such as nectar, but females need two to three protein meals for ovarian development and the maturation of the first egg batch. This protein is generally found in carrion, faecal

matter or active strikes (Barton-Browne *et al.*, 1987). *L. cuprina* occurs in low densities in the field and sources of protein may serve to bring the sexes together (Kettle, 1995).

It is known that a percentage of the population of *L. cuprina*, may mature its first batch of eggs without having to ingest a protein meal (autogeny). It remains a possibility that the same situation may apply to *L. sericata* in Britain, as it appears that only a small percentage of the wild population will preferentially strike the bodies of sheep. Strains of *L. sericata* with different physiological behaviour can exist within the species, and some of these may be more prone to striking sheep than others (Bates, unpublished data).

The size of adult flies and the reproductive potential of the females are determined by the amount of food consumed as larvae (maggots). In carcasses, where most blowfly maggots feed, *L. cuprina* is a poor competitor in the race to consume enough food to complete development compared with native brown blowflies (*C. augur* and *C. rufifacies*). *L. cuprina* has adapted to this poor performance by becoming almost an obligate parasite of sheep, virtually free of competitors. By the time other species are attracted to the struck sheep the *Lucilia* maggots are well developed (Levot, 2009a).

Phase 3 and 4: reproduction and attraction. Only gravid (egg-bearing) female flies are attracted to sheep. Sheep attract flies by the odours that are given off by excessive 'sweating' and/or decaying organic matter (including urine and faeces) in the fleece. Odours are detected by hair-like sensory organs on the third section of the antennae of the adult flies. Flies seem to be attracted to wet fleece preferentially over dry fleece, possibly as a result of the release of degraded amino acids or sulfides from wool proteins (Eisemann, 1996). Active infestations of *Dermatophilus congolensis* (mycotic dermatitis) and *Pseudomonas aeruginosa* (fleece rot) are recognized blowfly attractants, possibly owing to volatile bacterial decomposition products or plasma leakage via necrotizing damage to endothelial cells. Chewing lice (*Bovicola ovis*) infestations can lead to body strike as well; sheep that bite or rub to relieve irritation can often break the skin, exposing a moist protein source. Wounds resulting from detached ticks may become infected, also predisposing to blowfly strike. In South Africa, heavy infestations of the 'red-legged' tick (*Rhipicephalus evertsi evertsi*) may damage the udder and induce blowfly strike (Fourie *et al.*, 2001). Head strikes occur in horned sheep because of the accumulation of dirt and grease at the base of the horns, and wounds from fighting can also result in head strike, particularly in rams.

Evidence points to the possibility that some attraction factors are hereditary and that breeding ewes and rams continually struck on the body should be culled. Individual animals may be repeatedly struck as a result of the continual release of attractants, which encourages the flies to single out a particular sheep for oviposition. However, this may only apply to body strike. In a study investigating breech strike that spanned 12 weeks, 46 lambs were struck once, 20 lambs were struck twice and four of these lambs were struck three times. A genetic component of susceptibility to breech strike was unlikely in this case as twins of struck sheep were never struck themselves (Bates and Rankin, 2002). Ewes with deformed genital openings in which urine is directed onto the fleece, and ewes with narrow breeches that favour soiling, should also be culled.

Phases 5 and 6: landing and oviposition. Once the flies have been attracted to the sheep they have to land on the fleece in order to oviposit. As soon as the fly has landed on a suitable sheep it will, with the correct chemical stimulation, oviposit. Female flies have well-developed sensory organs on their feet and legs, which are used to find a suitable environment for egg laying. The odours that attracted the fly to the sheep are not necessarily the same as those that promote oviposition. Clean, dry fleece attracts female *Lucilia* spp., but does not stimulate oviposition, whereas soiled fleece will stimulate active oviposition, possibly owing to the presence of increased humidity and ammonia levels. Any source of ammoniacal decomposition will induce flies to oviposit.

Alkaline conditions are essential, and even bird droppings can illicit oviposition. Fleece bacteria have been shown to produce volatiles that could stimulate oviposition by *L. cuprina* (Merritt and Watts, 1978; Emmens and Murray, 1982, 1983).

Oviposition begins 5–9 days after adult flies emerge from the pupae (after two or three protein meals for ovarian development). Blowflies lay batches of eggs ('blows'), which minimizes desiccation. A female *L. sericata* can lay 2000–3000 eggs in nine or ten batches over a 3 week period, depending on the temperature. Female *L. cuprina* will lay two or three batches of eggs with about 200 eggs per batch. Eggs are laid individually at about 15 s intervals, egg laying taking about an hour per batch (Wilson and Armstrong, 2005).

Phase 7: hatching. If conditions are suitable, *L. sericata* or *L. cuprina* eggs generally hatch within 24 h, although incubation can be as short as 8 h. Prevalence of blowfly strike is weather dependent, with the majority of cases of body strike occurring during periods of high humidity or warm periods after heavy rain. A temperature of above 30°C, found on the skin and in the fleece, is required. First-instar (L_1) larvae cannot survive in fleece with a moisture content below 70–90%, and it has been shown that fleece moisture must be above 70% for at least 14 h for L_1 larvae to survive. Later instars are more tolerant. The optimum pH for development of *L. cuprina* is pH 8–9 (Guerrini, 1988).

Many egg batches are laid on sheep throughout the fly season, but if the fleece is too dry they will not hatch and develop into myiasis. The number of *L. cuprina* larvae needed to establish a strike is at least 1500. Not every egg will produce a viable larva and an established strike would be the result of egg laying by several flies. Breech strike is less weather dependent, the moisture supplied by urine and/or scouring being sufficient. Shearing temporarily stops infestation by preventing the build-up of excessive moisture. Other sources of moisture include saliva from licking and chewing the fleece owing to a skin irritation (resulting from ticks, lice, biting flies, seeds, etc.), or rain soaking the sheep through to the skin.

Phase 8: development. After hatching, *L. sericata* and *L. cuprina* larvae move down the fleece to the skin to feed on the protein-rich exudates produced by the skin, by skin fouling and by fleece rot. Larvae pass through three moults (instars) before pupating. In *L. sericata*, first-instar (L_1) larvae are 1.65 mm long at hatching and 3.5 mm long at moulting; second-instar (L_2) larvae range from 4.5 to 7.5 mm long at moulting. Third-instar (L_3) larvae are approximately 16 mm long.

Exudates from wounds wet the fleece, odours and maggot faeces attract further flies, and secondary and tertiary strikes can occur.

Phase 9: pupation. Fully fed third-stage (L_3) larvae drop off the sheep and enter a wandering stage before burrowing 1–4 cm into loose soil to pupate. Larvae usually fall off at night or in the early morning when ground temperatures are coolest. If the soil temperature is below 10–15°C, or if the soil is wet, *L. cuprina* maggots contract to a prepupa (Levot, 2009a). *Lucilia* spp. overwinter as prepupae. If the conditions that favour blowfly strike persist into the cooler months, larvae may continue to drop off into the soil for quite a few weeks but only develop into prepupae.

Although they may differ considerably in age, as the soil warms up (to above +7°C) in the spring, larval development will come into synchrony, and pupation then occurs (Levot, 2009a). The overwintering population will emerge simultaneously as adult blowflies in mid-to-late spring. If the overwintering population of flies encounter susceptible sheep, the next generation of flies will be more numerous (Levot, 2009a). If conditions remain suitable for fly strike these flies will produce a 'flywave'. Mortality in the overwintering prepupal population may exceed 90% as a result of waterlogging, freezing, parasitism or predation (by beetles, birds, ants and mice) (Levot, 2009a).

In the UK, four generations of *L. sericata* can be produced per season, with the last larvae overwintering to emerge as adults the following summer. In Australia, there can be approximately eight generations of *L. cuprina* a year (Kettle, 1995).

HOST SPECIFICITY AND BREED DIFFERENCES. Some breeds of sheep appear less susceptible to

strike. The woolless Wiltshire Horn is relatively resistant to strike, although the skin folds of the neck can be struck. Dark-fleeced sheep have been observed to be less prone to strike than those with white fleece, although this has not been proven scientifically. Shoulder and body strike appears more common in downland and downland-cross sheep, compared with coarse-fleeced hill breeds.

SEASONALITY. The prevalence of blowfly strike is weather dependent, with the majority of cases of body strike occurring during periods of high humidity or warm periods after heavy rain. In the south-east of England strikes can occur any time between March and December. Breech strike is less weather dependent, the moisture supplied by urine and/or scouring being sufficient.

PATHOGENICITY. Developing larvae lacerate and digest the skin using anterior hooks present on the oesophageal skeleton and secretory proteolytic enzymes. L_1 larvae cause relatively little damage to the host, as their mouthparts are too small for much traumatic damage to be initiated. L_1 larvae primarily produce proteolytic enzymes in order to degrade the epidermis of the host, whereas the later stages (L_2 and L_3) use the mechanical action of their well-developed mouthparts to rasp at the skin and cause damage to the dermis and underlying tissues. Larvae in primary strike cases may or may not invade the living tissue. Secondary flies (*Lucilia* spp., *Phormia* spp., *Chrysomya* or *Calliphora* spp.) are attracted by the smell of the primary lesion. *Calliphora* rarely initiates a strike on its own, although it has been identified as a primary strike fly in parts of north Wales. Similarly, the third wave of flies is attracted by the increasing lesions and secondary bacterial infection.

Lipid soluble ammonia, excreted by *Lucilia* larvae, is absorbed into the peripheral veins and lymphatic ducts of the host, and in severe cases the quantity absorbed may be sufficient to cause hyperammonaemia and alkalosis. Death can occur when ammonia concentrations exceed 200μmol/l in the venous blood (Guerrini, 1988). Such deaths can occur early in an infestation. It has also been demonstrated that high concentrations of unionized ammonia in the blood may suppress immunity by permanently damaging neutrophils and lymphocytes and depressing serum globulin production (Guerrini, 1997).

Sheep that are reinfested with *L. cuprina* show smaller wounds than sheep infested for the first time. Two mechanisms of resistance have been recognized: (i) early infestations (immediate hypersensitivity) in which the initiation of protein (antibody) leakage is controlled; and (ii) later infestations that may result in leakage of protein (antibody) that is capable of controlling larval survival. High levels of serum antibody are produced by infested sheep against the excretory/secretory products of *L. cuprina*, although the response does not peak until there have been four successive infestations.

CLINICAL SIGNS. Clinical signs of blowfly strike include agitation, worried behaviour and dejection, stamping of the hind legs, vigorous tail shaking, gnawing and rubbing at the breech or back. The gait may be uncertain or aimless, and the sheep may wander from the flock and hide. As the lesion develops, the odour is noticeable, and the wool becomes matted and discoloured. On close examination, the strike lesion appears as a foul smelling area of moist brown wool, often with early-stage maggots visible. If allowed to continue to develop, the affected area increases and wool is shed from the centre, with constant animal discomfort and loss of weight.

The actions of L_1 larvae are unlikely to elicit any clinical signs, but these will become obvious as the larvae go through to the second (L_2) and third (L_3) instars. Active L_2 and L_3 instars are relatively easy to locate and identify, and their presence should not be easily confused with other ectoparasitic diseases such as sheep scab. However, dead or treated blowfly lesions are often considered as suspicious and skin scrapings are often taken for scab diagnosis.

DIAGNOSIS. Diagnosis of blowfly strike is through observation for clinical signs and the isolation of blowfly larvae from a lesion (see Chapter 7).

PREVENTION OF SHEEP BLOWFLY STRIKE. All UK sheep farmers should be aware of the *Code of Recommendations for the Welfare of Livestock: Sheep* (Defra, 2003) that emphasizes the prevention and treatment of strike Effective chemical treatments are available, so a stock owner could face prosecution for animal cruelty (under the UK Animal Welfare Act 2006) if he/she neglects to prevent or treat for strike.

Regular and frequent flock observations. It is stressed that sheep can be struck even in the best-managed flocks, but prophylactic treatment, combined with careful monitoring of the flock on a regular basis, will prevent the lesions progressing. However, where husbandry is deficient, affected animals can be struck repeatedly and this will lead to a welfare problem.

Looking for infested animals is a time-consuming operation and must be carried out at least twice a day throughout the blowfly season; care should be taken to examine all sheep thoroughly. Even animals treated with a preventive insecticide need to be inspected at least once a day as all treatments break down eventually.

Selective breeding. Selecting sheep with reduced susceptibility to body strike (less fleece rot and body wrinkle in merinos) and breech strike (plainer breech, larger bare areas, less scouring) can be effective. Selection against 'hypersensitivity scouring' should be done using rams that have a low dag score, and 'daggy' ewes should be culled.

Trapping. Trapping (See Chapter 8) may reduce (but never eradicate) the numbers of blowflies attacking sheep and can be used to monitor fly activity, thus aiding the timing of preventive treatments, but these should not be a substitute for good husbandry (and in particular as a substitute for regular inspections).

Housing. Various authors have demonstrated that *L. sericata* will not enter areas of low light intensity; consequently, they are rarely encountered in houses or barns (Smith, 1986). Studies by the VLA have demonstrated that housing sheep during conditions of potential strike could be of benefit (Table 5.2).

Table 5.2. The effects of housing sheep in order to prevent blowfly strike by *Lucilia sericata* (Bates, unpublished data).

Housing	No. of sheep struck	Sheep struck (%)
Permanent shelter	1/16	6.2
Free access to shelter (shelter moved daily)	7/16	43.8
Free access to shelter (stationary)	4/16	25.0
No shelter	4/16	25.0

Shearing. Shearing temporarily stops infestation, but the incidence of body strike increases as the fleece grows sufficiently to favour survival of the maggots. However, this is not an excuse not to be vigilant. Shorn sheep with excessively folded skin (particularly on the neck) can still be struck. Unshorn sheep and lambs are continually at risk.

Crutching and dagging. Crutching, the removal of wool from around the tail and between the rear legs, and dagging, the removal of soiled wool around the breech and inside the back legs, provide an effective control of breech strike. The operation is best started in May and must be repeated every 4–6 weeks for it to remain effective.

Mulesing. The Mules operation was developed in Australia in 1931. Mulesing is the surgical amputation of the wrinkled skin from the perineum and the breech, widening the bare surface of the perineum, thus rendering it less susceptible to breech strike in merino sheep (Dun, 1964). Mulesing can reduce breech strike by 80–90% (Blood and Radostits, 1989), although there can be a high incidence of breech strike associated with scouring in radically mulesed sheep with very short (butted) tails (Morley *et al.*, 1976). The practice of mulesing is common in Australia. It is, however, controversial, and is considered to be both painful and cruel. The Australian Veterinary Association (AVA) recognizes the welfare implications but, in the absence of more humane alternatives for preventing breech strike, accepts that the practice should continue.

Tail docking. Tail docking can reduce the incidence of strike. Tail docking (tail amputation) of lambs is a routine procedure on most farms in the UK and is considered necessary to prevent faecal soiling and prevent blowfly strike. However, it can be considered to be a painful mutilation. French *et al.* (1994b) documented that many studies on lamb tail docking had been carried out, many with particular reference to its role in preventing fly strike, but that none of these studies included undocked controls. However, in a controlled field study in the UK, these authors demonstrated that 1.3% of docked lambs presented with breech strike, compared with 6.6% for undocked lambs. There may be breed differences in susceptibility to breech strike, as hill breeds in the UK are traditionally left undocked. In Australia, Morley *et al.* (1976) reported that there was a slightly increased risk of faecal soiling in undocked lambs, increasing the risk of blowfly strike.

A short tail may also be able to ward off flies (it is only the top portion of the tail that is actually mobile, as seen in suckling lambs), and tail docking can either protect or predispose sheep to breech strike according to the site of amputation. Docking lambs' tails very short strongly predisposes radically mulesed ewes and wethers to faecal soiling and breech strike (20% struck). Radically mulesed sheep with tails docked midway down to the vulval orifice in ewes, and to the corresponding length in wethers, were rarely struck (3%) and did not need crutching to prevent breech strike associated with scouring or urine staining (Watts and Luff, 1978). Similarly, there are substantially fewer breech strikes in sheep with long-docked tails (ending at or just below the tip of the vulva in ewes) than in sheep with butted (short-docked) tails. Riches (1941, 1942) concluded that long-tail docking protected against strikes affecting the tail but not against strikes affecting the breech area. French *et al.* (1994b) found that long-tail docking prevented strikes at both sites. Under UK law, enough tail must remain undocked to cover the vulva in ewes and the anus in rams; this is equivalent to the long-tail docking in Australia. Also, trimming wool around the opening of the prepuce of rams will reduce the incidence of pizzle strike.

Control of other parasites and infections. Good husbandry in the prevention of other skin infections will greatly benefit strike control. Mycotic dermatitis (lumpy wool) can be a predisposing factor to strike. Helminth parasites should also be controlled in order to decrease the probability of scouring and the incidence of breech strike. In Australia, the incidence of breech strike was reduced from 50% to 5% after drenching for parasitic worms (Morley *et al.*, 1976). The control of scouring caused by changes in diet and digestive disturbances resulting from lush grass is also essential, and research has shown that vaccination against *P. aeruginosa* can protect against severe fleece rot and consequently against blowfly strike as well (Burrell, 1985).

Burying carcasses. Burying all carcasses (small and large animals) can minimize the ovarian development of adult female flies and the build-up of alternative generations of flies. This is now a legal requirement in the UK under the *EU Animal By-Products Regulations* (2003), which requires that all fallen stock must be incinerated by an authorized contractor. French *et al.* (1994a) recorded a high strike prevalence associated with on-farm carcass disposal.

Selective culling. Some evidence points to the possibility that some attraction factors are hereditary and that breeding ewes and rams which are continually struck should be culled, as should ewes with deformed genital openings, where urine is directed onto the fleece, or ewes with narrow breeches that favour soiling.

Obligate myiasis

*Nasal botflies (*Oestrus ovis*)*

Larvae of the nasal botfly, *O. ovis,* are sinonasal parasites of wild and domestic sheep and goats (Zumpt, 1965; Capelle, 1966). The condition, known variously as oestrosis, nasal myiasis, parasitic rhinitis, head grub, 'grub in the head', 'sheep warble' or 'false

gid' is found in all the major sheep-rearing countries of the world.

DESCRIPTION. Adult *O. ovis* are 10–12 mm long and have a dark grey thorax with four small indistinct stripes. The abdomen is short with silvery reflections and irregular dispersed flecks.

WORLD DISTRIBUTION. *O. ovis* is found in hot arid regions of Europe, North and South Africa, the Middle East, Asia, Australia, New Zealand and North America. In Spain, 98% of flocks have been shown to be affected, with an in-flock prevalence of 71% (Rojo-Vásquez *et al.*, 2007). In central Ethiopia, Yilma and Genet (2000) recorded 77.4% of sheep and 72.9% of goats as infested.

The fly has been recorded in the UK (Collyer and Hammond, 1951), and Rogers and Knapp (1973) cited Clark (1796) removing mature larvae from the frontal sinuses of English sheep. An abattoir survey for the whole of Britain revealed a national incidence of 0.75%, with *O. ovis* most prevalent in the warmer counties south of latitude 52°, which may represent the northernmost range of the species (Bates, 2007a). A prevalence of 8.7% was recorded for England and Wales; the prevalence was 11.8% in the English and Welsh counties where *O. ovis* was found (Bates, 2007a). Localized surveys covering south Wales and south-west England recorded prevalences of 0.5% and 0.75%, respectively, but a survey in Surrey and West Sussex revealed a prevalence of 16.6%. In one flock, 51.3% of ewes presented signs of oestrosis (Bates, 2007a). Areas further north could be foci of infestation through the importation of infested sheep from the endemic south, with warm summers allowing the establishment of temporary populations.

LIFE CYCLE. Adult *O. ovis* do not feed and are active in hot, dry weather for up to 37 days (Mitchell and Cobbett, 1933; Fallis, 1940; Ternovoi and Mikhailenko, 1973; Chhabra and Ruprah, 1976). Female flies are larviparous and during their life can deposit up to 500 larvae (Zumpt, 1965). In Baja-California, Mexico, larviposition was observed to occur when temperatures rose above 20°C, was optimal from 25 to 28°C and reduced from 34 to 35°C, even on cloudy days; wind could be calm and humidity could range from 44% to 100%, but optimal humidity was from 65% to 85% (Cepeda-Palacios and Scholl, 2000).

How the flies are attracted to sheep and goats to larviposit is not known. Anderson (1989) showed that deer botflies (*Cephenomyia apicata* and *Cephenomyia jellisoni*) were attracted and induced to larviposit on the lips and muzzles of deer models baited with carbon dioxide and carbon dioxide plus 1-octen-3-ol and deer trail scent. Similar attraction and larviposition attractants may be produced by sheep and goats. Ternovoi and Mikhailenko (1973) demonstrated that captured adult *O. ovis*, when released into sheep pens, remained at the site of release; they also demonstrated that adult flies released at possible breeding sites in grazing areas were found within a few days in sheep pens and buildings up to 6.0 km away. This suggests that an attractant released from concentrations of sheep was extremely important. Cepeda-Palacios and Scholl (2000) observed no strikes in pens of goats with fewer than 45 animals, but the number of strikes increased when the numbers of goats increased to above 80 per pen. Thus, the concentration of attractants is also very important.

The gravid female fly attacks by darting quickly at the nostrils of a potential host, depositing larvae in or on the nostrils on each successive dart. The orbits may also be struck (Cobbett and Mitchell, 1941). Most strikes occur just before dusk, with a few in the morning (Cepeda-Palacios and Scholl, 2000). First-stage (L_1) larvae are 1.3 mm long on deposition (Fig. 5.6). They enter the nasal cavity and attach to the mucus membranes by 22–25 terminal hooks. L_1 larvae are generally found in or on the nasal turbinates, but sometimes in the nasopharynx. The larvae feed on mucus and desquamated cells, using their strong cephalo-skeletons (Zumpt, 1965). L_1 larvae conceal themselves within the folds or crevices of the dorsal

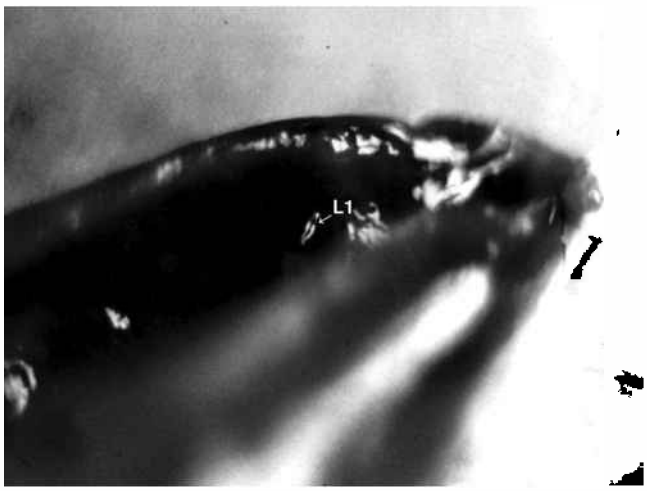

Fig. 5.6. First-instar (L_1) larva (indicated by the arrow) of the nasal botfly (*Oestrus ovis*) on the tip of the nasal turbinate cartilage (Photo © P. Bates).

and/or ventral turbinate bones, from which the host is unable to expel them.

Second-stage (L_2) larvae are 3.5–12.0 mm long and white with ventral rows of 'curry comb'-like spines and appear to have a shorter period of activity than L_1 larvae; larvae are only isolated between March and July, mainly from the nasal cavity or the turbinate bones (and to a lesser extent from the ethmoid process or frontal sinus). Cobbett and Mitchell (1941) reported that L_1 larvae enter the frontal sinuses via the ethmoid process before moulting into the L_2 stage. L_2 larvae pass into the frontal or maxillary sinuses, where they mature into the third-stage (L_3) larvae (Jensen and Swift, 1982).

L_3 larvae are 20 mm long, yellow when young, and turning to light brown with broad transverse dark stripes on the dorsum upon maturing (Fig. 5.7). The ventral segments bear rows of strong spikes. When mature, the L_3 larvae re-enter the nasal cavity, where they are sneezed out of the host. Upon reaching the ground, mature L_3 larvae pupate within 24 h, forming a black pupa 15–16 mm long. The pupal period can exist for 17–70 days. Times of 27–28 days have been recorded in the summer, but these can be longer (49–66 days) in the autumn/winter. Rogers *et al.* (1968) demonstrated that temperature is an important factor in emergence, with an optimum of 27°C. Pupae exposed to temperatures below freezing for brief periods survive, but constant temperatures below 16°C and above 32°C can be lethal.

HOST SPECIFICITY. Adult female *O. ovis* have also been recorded depositing larvae in dogs (Luján *et al.*, 1998), European ibex (*Capra ibex*) (Zumpt, 1965), North American bighorn sheep (*Ovis canadensis*) (Capelle, 1966) and humans (James, 1947). The parasite has also been cultured experimentally in rabbits (Taronik, 1990).

Papadopoulos *et al.* (2006) investigated the host preference of *O. ovis* between sheep and goats in mixed flocks in Greece that were kept together under the same husbandry conditions and with potential exposure to *O. ovis*. Antibodies specific to *O. ovis* were measured by ELISA. A total of 48.6% of sheep and 17.9% of goats were found to be seropositive to *O. ovis*. A very significant difference ($P = 0.001$) was observed between the infestation rates of sheep and goats. Dorchies *et al.* (2000), investigating infestation rates in sheep and goats in Pezanas, southern France, recorded 43.4% of sheep

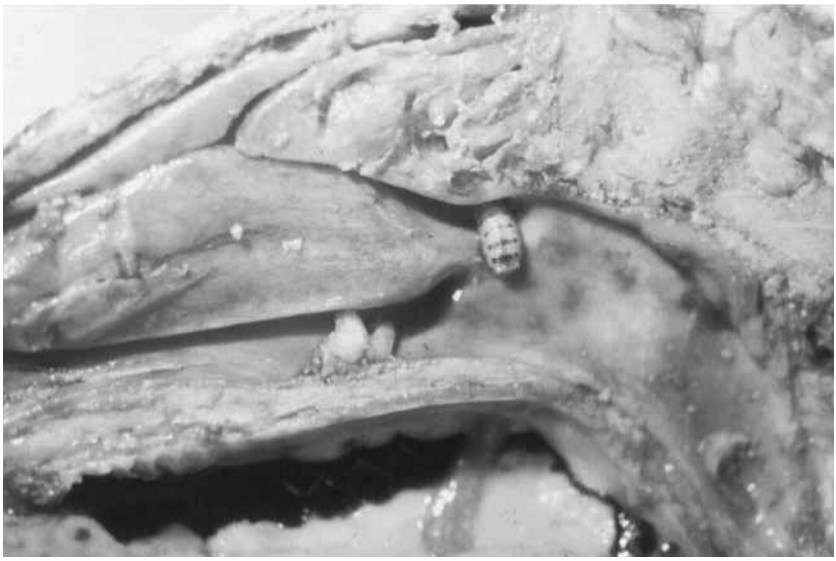

Fig. 5.7. Third-instar (L_3) larvae of the nasal botfly (*Oestrus ovis*) *in situ* in the nasal cavity (Photo © P. Bates).

and 28.4% of goats infested with *O. ovis*. The mean number of larvae per head was also higher in sheep than in goats, with a mean of 10.9 for sheep and 5.3 for goats. Thus, sheep appear to be more susceptible to *O. ovis* than goats.

SEASONALITY. In Britain, there appears to be only one period of fly activity between May and October (Bates, 2007a), comparable to the middle zone of the former USSR (Antipin *et al.*, 1959), with two overlapping generations of flies and subsequent larval deposition in May to June and July to October (Bates, 2007a). Adult female *O. ovis* (emerging in July to October) appear to deposit first-instar (L_1) larvae in the late summer (August/September) and these larvae are quiescent in the nasal turbinates until the following March, when they begin developing into second-instar (L_2) and third-instar (L_3) larvae. L_1 larvae appear to be present in the nasal turbinates (but sometimes in the nasopharynx or ethmoid process) throughout the year, albeit in lower numbers in early to mid summer (May, June and July). Low numbers during these months may indicate the 'change over' between generations of larvipositing adults. In Tuscany, Italy, a high percentage of L_1 larvae were observed between September and February (Alzieu and Chiriasoli, 1990).

Clinical signs of oestrosis were also most prominent in May, appearing in flocks as early as March but still recorded in November. The prevalence of *O. ovis* varies from year to year. Higher incidences of infestation may follow years with unusually hot summers and thus a greater number of active adult flies challenging sheep.

DAMAGE. Damage by *O. ovis* can be through the direct action of the feeding larvae or by the irritation caused by larvipositing flies.

Damage due to feeding larvae. In the majority of sheep and goats, sinuses infested with L_1 larvae show little or no damage (Jensen and Swift, 1982). Irritation of the mucus membranes by toxic excreta and by cuticular spines and oral hooks, through migrating larvae can cause mild catarrhal discharge and sneezing (Cobbett and Mitchell, 1941). Examination of a flock presenting with signs of oestrosis recorded 48.6% of ewes demonstrating no clinical symptoms whereas 51.3% demonstrated clinical symptoms attributed to *O. ovis* infestation, i.e. mucosal

nasal discharge. Adult rams or ram lambs grazing at a site nearby demonstrated no clinical symptoms, yet all were shown to be infested with L_1 larvae at post-mortem (Bates, unpublished data).

A number of sheep and goats can present with severe damage caused by *O. ovis* infestation, which can be possibly fatal. Bacterial invasion can lead to the thickening and inflammation of the mucus membranes, progressing to breathing difficulties and possibly death. Larvae can sometimes penetrate the bronchi (Cobbett and Mitchell, 1941). Membrane thickening can also prevent the escape of the larger L_3 larvae, which die deep *in situ* in the sinuses. The resulting abscess may cause severe illness or even death. One or more dead larvae can produce oedema, thickened membranes and exudate-filled cavities (Jensen and Swift, 1982). Dead larvae in the sinuses can also elicit an allergic and inflammatory response resulting in interrupted feeding, but secondary bacterial infections are the probable cause of death (Cobbet and Mitchell, 1941). Meleney *et al.* (1962) observed that in older ewes it was not uncommon to find abscessation of the nasal passages caused by the death of the outward migrating L_3 larvae, trapped in the diverticula of the dorsal turbinates. Rogers and Knapp (1973) suggested that the longer L_3 larvae remain in the head, the higher the larval mortality rate. *O. ovis* larvae in the upper respiratory tract are associated with limited but significant increases in the numbers of inflammatory cells in the lower respiratory tract (Hoste *et al.*, 2002).

O. ovis has also been incriminated as a possible predisposing factor to respiratory disease such as pleuropneumonia (Ranatunga and Rajamahendran, 1972). Dorchies *et al.* (1993) reported that the presence of pulmonary abscesses was less frequent in treated sheep than in untreated animals and suggested that permanent antigen release related to continuous reinfestation during the grazing season activates a causative viral agent. *O. ovis* infestation has also been associated with *Pasteurella* infection and copper deficiency (Tarry, personal communication).

Antipin *et al.* (1959) and Parihar (1989) postulated that *O. ovis* larvae could enter the brain. Bergeaud *et al.* (1994) recorded 4.9% of infested sheep in the Aveyron area of south-west France with concomitant pituitary mucosal tumours. *O. ovis* may induce pathological changes in the mucosal membranes of organs that are some distance away from the primary site (Yacob *et al.*, 2002).

Damage due to adult flies. Cobbett (1956) described damage due to adult *O. ovis* as the source of greatest loss. Animals become nervous and are constantly alert and spend much time avoiding the flies ('gadding'), and in doing so are prevented from grazing and resting during the daytime.

INFESTATION RATES. Rates of infestation are dependent on the numbers of adult fertilized females depositing larvae (Meleney *et al.*, 1962). This finding was supported by Pandey (1989) in Zimbabwe, who observed that a low infestation rate was caused by a low population of adult flies.

A number of factors can affect the rate of infestation of *O. ovis*, namely: (i) the age and immune status of the host; (ii) the general health of the host; (iii) the breed and physical structure of the host; and (iv) the local climate. These are discussed below.

Age and immune status of the host. Severe symptoms of oestrosis are generally observed in the adult host. Older goats (above 1 year old) have been shown to have a significantly ($P < 0.001$) higher infestation rate (87.5%) than younger goats (under 1 year old) (70.8%) (Yilma and Genet, 2000). Conflicting opinions exist as to the susceptibility of lambs to *O. ovis* infestations. Meleney *et al.* (1962) observed a lower infestation rate in lambs and attributed this to the fact that lambs are more agile in avoiding larval deposition and can be seen hiding from fly activity by burying their noses in their mothers' wool. Yet Rogers and Knapp (1973) noted that larvae mature more rapidly and in greater numbers in lambs than in older animals. This could be due to older animals having been exposed to infestation before and developed a form of acquired resistance. Evidence for the effects of host immunity has been collected by Bautista-Garfias (1988) in Mexico and Marchenko and Marchenko (1989) and Marchenko *et al.* (1991) in the former

USSR. Bautista-Garfias *et al.* (1982, 1988) demonstrated that circulating antibodies are produced against *O. ovis*, and Marchenko and Marchenko (1989) deduced that the host immune reaction controlled the extent of infestation. The longer the larvae remained in the sinuses, the greater their mortality, with only 10–20% of larvae reaching pupation (Antipin *et al.*, 1959). Marchenko *et al.* (1991) observed that antibody titres depended on the parasite biomass, instar and host age, with antibody response to primary infestations more intense in young lambs than in older animals. It is not known how long this immunity remains or whether winter infestations prevent infestations only in the following summer or for successive years. It is probable that concurrent immunosuppressive diseases (e.g. tick-borne fever, TBF) may also increase the likelihood of *O. ovis* infestations.

Health of the host. Unthrifty animals and animals with lowered immune responses are more susceptible to infestation than healthy animals.

Breed. Meleney *et al.* (1962) postulated that the variations in the capacity of the nasal and frontal sinuses in different breeds of sheep, and within individual sheep, may be factors in the extent of infestation by *O. ovis*. In some sheep, the sinuses may be too narrow or have membranes so thickened that no larvae can enter. Miller *et al.* (1961) recorded that the limited size of the frontal sinus in some breeds allows only two to eight larvae to occupy the sinus at any one time. In Yucatan, Mexico, Murguía *et al.* (2000) postulated that nose colour may be an important factor in host selection, with infestation rates in dark-nosed sheep significantly higher ($P<0.05$) than in spotted-nosed sheep.

Climate. In Britain, the climate appears to be the primary factor governing the distribution of *O. ovis*, with the parasite endemic in the warmer counties south of latitude 52° from the Lleyn Peninsular in north Wales in the west to the Wash in the east. This distribution may represent the northernmost range of the species. Climate change may change this present distribution, increasing prevalence in the south and allowing the parasite to spread northwards. Cobbett and Mitchell (1941) showed that climate governs the numbers of generations of *O. ovis* per year. In areas of moderate winters, adult flies are active throughout the year, except in January and February; the third-instar (L_3) larvae are expelled all year round. However, in areas with cold winters, adult flies are only active on the dry warm days of summer, and larvae are expelled only during one or two specific periods. The life history of *O. ovis* deduced for Britain suggests that third-instar (L_3) larvae are only expelled and pupate between March and August, and that the adult fly is only on the wing between May and October (Bates, 2007a).

Larval development ceases in the autumn and winter and first-instar (L_1) larvae are quiescent; they will not migrate to the frontal sinuses until spring and summer. In the spring and summer, it is possible to complete the transition from L_1 to L_3 in 25–35 days (Bedford, 1925b; Fallis, 1940; Cobbett and Mitchell, 1941). Thus, larvae deposited in the summer develop quicker and possibly produce more severe symptoms. Cobbett and Mitchell (1941) also noted that there were marked variations in the development time between larvae from the same deposit; while some larvae took 25–35 days to reach pupation, others remained in the L_1 stage for 9 months.

Kettle (1995) reported that the site for overwintering was the ventral turbinates or the proximal end of the dorsal turbinates. It has been suggested that the lower temperature of inhaled air in winter renders the first-instar (L_1) larvae dormant. Rogers *et al.* (1968) demonstrated that for larval depths of 50 mm or more, external temperatures as low as –12°C may not alter nasal temperatures sufficiently to produce quiescence in *Oestrus* larvae. Dormancy may be controlled by the effects of photoperiod or temperature on the developing fly in the puparium or on the newly hatched fly, causing it to produce larvae capable of retarded development or dormancy. The seasons also affect the rate of development. Larvae in lambs maintained at high temperatures have a greater survival

rate and rate of development than larvae from lambs at lower temperatures, although smaller populations of larvae from the lower temperatures produce more larvae to maturity (Rogers and Knapp, 1973).

Larvae of *O. ovis* are exclusively parasitic, inhabiting a protected environment within the sheep. During the brief adult life of *O. ovis*, mating, egg maturation and larviposition must be achieved. Adult flies have atrophied mouthparts and, being unable to feed or ingest water, must rely on reserves accumulated during the larval stages. Adults of *O. ovis* are therefore vulnerable to adverse climatic conditions. Tarry (1978) suggested that in extremely hot conditions adult mortality through desiccation and adverse thermal effects could be high. The depth of soil penetration achieved by prepupating third-instar (L_1) larvae is not known. The deeper they penetrate the lower the rate of successful emergence, as the surface layer of soil may be difficult to penetrate. Periods of excessive rainfall can destroy both pupae and emerging adults (Tarry, 1978). Bright sunshine is important for successful mating and host finding will be greater at optimum temperatures (Tarry, 1978). Observations on cattle warble flies (*Hypoderma* spp.) have suggested that a lowered infestation rate follows a cold wet summer (Beesley, 1966).

A combination of all the factors discussed above may allow for mortality within the host. Grunin (1957) observed that only 3–4% of L_1 larvae reach maturity. Rogers and Knapp (1973) estimated that the mortality during immature stages was 90.2–93.3% for L_1 and 98.5–99.1% for the L_2 generation.

CLINICAL SIGNS. Clinical signs of oestrosis include nasal discharge (rhinitis), which is sometimes haemorrhagic, sneezing, wheezing breath, snorting, bellowing, teeth grinding, head shaking, unthriftiness, rubbing the nose against the ground, head tossing, nervous excitability, 'gadding' (stampeding) and sometimes blindness, pneumonia and death. Gadding can often lead to self-inflicted wounds.

Larvae (particularly L_1 larvae) can also be recovered from animals not demonstrating any clinical signs (Bates, unpublished data).

Infested sheep seek cool, damp, shade not frequented by the flies, often ramming their noses against the ground. Loss of appetite and emaciation have been recorded, as has conjunctivitis through larviposition in the orbits (Cobbett and Mitchell, 1941). Partial blindness was recorded in a field case in the UK (Bates, unpublished data).

ZOONOSES. Humans can be accidental hosts to *O. ovis*. First-stage (L_1) larvae are generally deposited in the eye, rather than the nasal passages, although they never develop beyond the L_1 stage. Human oestrosis is a common problem in countries bordering the Mediterranean, the Middle East and the southern states of the former USSR (James, 1947; Dar *et al.*, 1980; Omar *et al.* 1988; Garzozi *et al.*, 1989). Human oestrosis has also been recorded in New Zealand (MacDonald *et al.*, 1999). In Britain, a small number of cases of human oestrosis are reported each year, but a larger number may go unreported, and the incidence of human oestrosis may increase with the threat of climate change.

Symptoms of oestrosis in humans have included the sensation of a foreign body, irritation, redness and photophobia, all symptoms that resolve on removal of the larvae (MacDonald *et al.*, 1999). Some patients can present with nasal symptoms, including sneezing, nasal discharge and epistaxis (MacDonald *et al.*, 1999). Human oestrosis can result in opthalmomyiasis – either opthalmomyiasis externa, where the larvae remain as superficial parasites, or opthalmomyiasis interna, where the larvae burrow into the sclera and penetrate deep into the eyeball, causing considerable damage (Omar *et al.*, 1988). One theory for human involvement is that gravid females do not find a sheep or goat host quickly enough and attack humans out of desperation, especially those handling sheep or goats.

DIAGNOSIS. Diagnosis of oestrosis is through the observation of clinical signs or by the actual observation of live L_3 larvae in water or feed troughs or, more commonly, the demonstration of L_1, L_2 and/or L_3 larvae by

post-mortem examination of the sinuses. It is important to note that overwintering larvae in the sino-nasal area do not show clinical symptoms (Cobbett and Mitchell, 1941; Pandey and Ouhelli, 1984).

Symptoms of oestrosis have been confused with those described for scrapie. They may also be confused with the symptoms of ergotism (Kettle, 1973), gid (*Coenurus* infection), listeriosis and sheep scab (*Psoroptes ovis*). Symptoms may also be similar to those described for ovine psoroptic otoacariasis by Bates (1996a). Oestrosis should also be considered in the differential diagnosis of bluetongue disease (Bates, 2007b).

Screw-worm flies as agents of wound myiasis

The three major species of obligate parasitic fly larvae found in wound myiasis are the New World screw worm, *Cochliomyia hominovorax*, the Old World screw worm, *Chrysomya bezziana*, and Wohlfahrt's myiasis fly, *Wohlfahrtia magnifica*. The human botfly or torsalo (*Dermatobia hominis*) has also been recorded infesting sheep in South America.

C. hominovorax is endemic to parts of Central and South America, but has been eradicated from the USA, Mexico and several Central American countries. It has been recorded attacking sheep and goats (as well as cattle, water buffaloes, horses, pigs, dogs, camels and elephants) (James, 1947).

C. bezziana occurs throughout much of Africa, the Middle East, the Indian subcontinent, South-east Asia and Papua New Guinea. It has been recorded attacking sheep and goats (as well as cattle, horses, pigs and dogs) (Zumpt, 1965). Adult females deposit 150–500 eggs at sites of wounding or in body orifices (the nose, ear and urinogenital passages). The larvae hatch after 18–24 h, moult after 12–18 h and again about 30 h later. They feed for 3–4 days and then drop off the host to pupate. The pupal stage lasts for 7–9 days in tropical conditions, but for up to 8 weeks in the subtropical winter months (Zumpt, 1965).

W. magnifica is an obligate parasite of warm-blooded vertebrates in south-eastern Europe, Asiatic Russia, the Near East and North Africa. Between 1999 and 2002 a problem outbreak occurred throughout the main livestock-producing regions of the island of Crete (Greece). These areas contained large numbers of sheep and goats, and lack of knowledge of the parasite was probably responsible for the severity of the outbreak (Sotiraki *et al.*, 2002). Adult *W. magnifica* feed on flowers and are active during the bright, hot period of the day (10.00–16.00 h). *W. magnifica* is a viviparous or an ovoviviparous fly, depositing 120–170 active first-instar (L_1) larvae near wounds or body openings of sheep and goats (as well as humans, cattle, horses, donkeys, pigs, dogs, camels and geese). Camels and sheep appear to suffer the most, and Hall and Farkas (2000) observed that *W. magnifica* was found mostly on sheep. Larvae feed and grow rapidly, burrowing into the tissue and causing extensive damage that may prove fatal (Kettle, 1995). Larvae mature in 5–7 days and then leave the wound to pupate in the soil (Zumpt, 1965; Kettle, 1995). Adults emerge if the temperature is above 12–14°C. *W. magnifica* can overwinter as diapausing pupae, and a diapause of 6–10 months has been recorded in Kazakhstan (Akhemetov, 1990).

CLINICAL SIGNS. The clinical signs of screw-worm attack are ragged, foul-smelling lesions (containing screw-worm larvae), secondary infections and strikes, constant licking of the wound, fever, debilitation, lethargy and loss of appetite, decreased growth rate and mortality.

*Goat warbles (*Przhevalskiana *spp.)*

Zumpt (1965) described three species of *Przhevalskiana* infesting sheep and goats, *Przhevalskiana crossii*, *Przhevalskiana silenus* and *Przhevalskiana aegari*. However, genetic studies on third-instar (L_3) larvae using nine separate methods have demonstrated that differences between the three morphotypes are all variations within the species *P. silenus* (Tassi *et al.*, 1986). *Przhevalskiana* spp. have been recorded infesting goats in Afghanistan, Albania, Cyprus, Greece, Iran, Iraq, Israel, Italy, Sicily,

Pakistan, the Punjab, Saudi Arabia, Siberia, Syria, Turkey and the former Yugoslavia. Recorded infestation rates include 53–94% for Anatolia (Turkey) (Sayin *et al.*, 1973b; Sayin, 1977), 24% for Albania (Tagari and Manehosa, 1973), 36.5% for Iran (Navidpour *et al.*, 2007) and 22–25% Iraq (Abul-Hab and Al-S'adi, 1974). In Italy and Greece, infestation rates exceed 70% (Puccini and Giangaspero, 1985; Liakos, 1986). Papadopoulos *et al.* (1996) assayed sera from 4900 goats using ELISA (with antigen derived from the bovine warble fly, *Hypoderma lineatum*), and found that an average of 49.2% (range 5–84%) of Greek goat herds were infested with *P. silenus*.

LIFE CYCLE. Adults of *P. silenus*, like all Oestridae, lack mouthparts, relying on the food reserves accumulated in the larval stages. Studies in Anatolia (Sayin *et al.*, 1973a; Sayin, 1977) showed that adults are active from April to June, and that after mating, the females lay eggs on the hairs of the hind legs (mainly the tarsal femoral regions). Larval migration is exclusively subcutaneous, with larvae reaching the back between late December and early February. Pupation occurs between February and April, according to weather conditions (in Anatolia, Sayin *et al.*, 1973a and Sayin, 1977; in south-eastern Italy, Puccini *et al.*, 1985, 1986).

DIAGNOSIS. *P. silenus* infestations are usually detected through palpation for second (L_2) and third (L_3) instar larvae on the backs of live goats, or through confirmation of the presence of live larvae under the skin at post-mortem (Navidpour *et al.*, 2007). The use of an ELISA is being investigated, with a sensitivity and specificity calculated at 86.6% and 98.9%, respectively, in the first 3 months of infestation, while the larvae are in the first (L_1) stage (Navidpour *et al.*, 2007).

6

Fleas (Siphonaptera)

Fleas are wingless ectoparasites of birds and mammals that belong to the insect family Siphonaptera. Over 1790 flea species have been described, with the majority (93%) occurring on mammals and only 7% occurring on birds.

All fleas have the same basic structure (Fig. 6.1), so identification to genus or species level requires specialist knowledge. However, the presence or absence of combs of heavy spines (ctenidia), either near the mouthparts (oral or genal ctenidium) or immediately behind the head (the pronotal ctenidium) can aid in the basic identification of adult fleas.

Fleas are laterally flattened to minimize damage from their hosts and are nidicolous (i.e. associated with nest-dwelling animals). Although extremely rare on ranging ungulates and primates they are becoming an increasing problem on housed sheep and goats in Ethiopia (Yacob *et al.*, 2008), Iran (Yakhchali and Hosseine, 2006), Israel and Kenya, Nigeria and Tanzania (Kusiluka and Kambarage, 1996).

The species most associated with small ruminants is the cat flea (*Ctenocephalides felis*), and to a lesser extent the dog flea (*Ctenocephalides canis*). The sticktight flea of poultry (*Echidnophaga gallinacea*) has been recorded infesting small ruminants in sub-Saharan Africa (Kusiluka and Kambarage, 1996). In Amhara Regional State in Ethiopia, 8.1% of goats were shown to be infested with *Ctenocephalides* spp. (Sertse, 2008), and 13% of sheep and 16.8% of goats have been reported to be infested with *C. felis* in Urmia, Iran (Yakhchali and Hosseine, 2006).

The 'alakurt' fleas (*Dorcadia ioffi* and *Vermipsylla alakurt*) parasitize ungulates, particularly sheep (as well as horses and yaks) in Central Asia, often in very large numbers. Alakurt fleas can cause anaemia, hair loss, retarded growth, unthriftiness and occasionally death, especially in newborn lambs (Durden and Hinkle, 2009).

The Life Cycle of *Ctencephalides* spp.

Fleas undergo complete metamorphosis, with egg, larval, pupal and adult stages. The life cycle is greatly influenced by temperature and humidity – the higher the temperature and humidity the quicker the cycle. Adult fleas live in a relatively stable environment on the host. However, the developing stages may experience much more extreme physical conditions off the host. Very low (<3°C) or high (>33°C) temperatures and extremely high or low humidity are lethal to them (Krämer and Mencke, 2001).

Eggs are relatively large (0.3–0.5 mm long), oval, whitish and non-sticky, easily falling off the host to the ground.

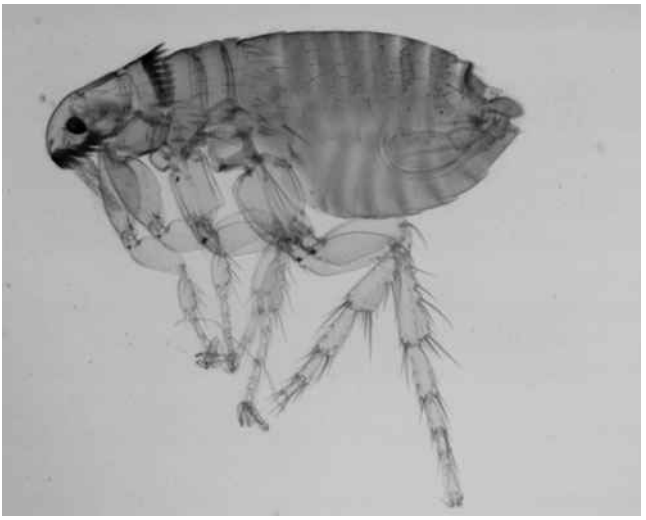

Fig. 6.1. The cat flea (*Ctenocephalides felis*), showing the position of the genal comb (near the mouthparts) and the pronotal comb (behind the head) (Photo © Leon Fourie/Clinivet).

Egg production begins 2 days after the first blood meal and females can lay 13–24 eggs/day and 158 over their lifetime (Krämer and Mencke, 2001). Optimal oviposition occurs in the final 2–3 days of their lives. The eggs hatch within 1–10 days, depending on the temperature and humidity (Krämer and Mencke, 2001).

First-stage (L_1) larvae use a chitin tooth located on the head for splitting the egg. Larvae are semi-transparent, whitish, vermiform and with a distinct yellow-brownish head, 13 body segments and no appendages (Fig. 6.2). The end segment bears a circlet of backward-directed bristles which, together with the anal struts on the last segment, enable the larvae to be vigorously active. Larvae undergo three moults and can measure 4–5 mm when fully grown. They have no eyes but are negatively phototaxic, and burrow into the nest or substrate. Larvae feed on organic debris, particularly adult faeces, and this is supplemented by adults passing undigested blood. Larvae are most susceptible to humidity requiring 50% humidity for a 50% survival (Krämer and Mencke, 2001). Adult vermipsyllid (alakurt) fleas in the genera *Vermipsylla* and *Dorcadia* feed on large ungulates, ovipositing randomly into the environment, where the resulting larvae must actively search for organic matter suitable to eat (Durden and Hinkle, 2009).

Mature third-stage (L_3) larvae empty their guts and enter the prepupal phase by constructing a thin, ovoid, loosely woven pupa (3 mm long by 1 mm wide) which is coated with particles of debris picked up from the surroundings for camouflage. The adult flea develops within the pupa. The pupa offers no protection against desiccation, particularly when the humidity falls below 45%. At 30°C and 78% humidity maximum pupation occurs after 7 days. Fully formed adult fleas (pre-emergent adults) stay in the pupa until stimulated to emerge, and can remain in the pupal stage for up to a year.

Adult fleas emerge from the pupae using the frontal tubercle on the head. Adult fleas are approximately 1–6 mm in length, mahogany brown in colour and recognized by their ability to jump when disturbed. Females tend to be larger than males of the same species, and there are generally more adult females than males in a population; females also live longer. Once on a suitable host, adults will remain on that host as permanent ectoparasites. Once they fall off the host, they can only survive 1–4 days. It is not the adult flea that presents the main problem in flea control, as in sheep or goat

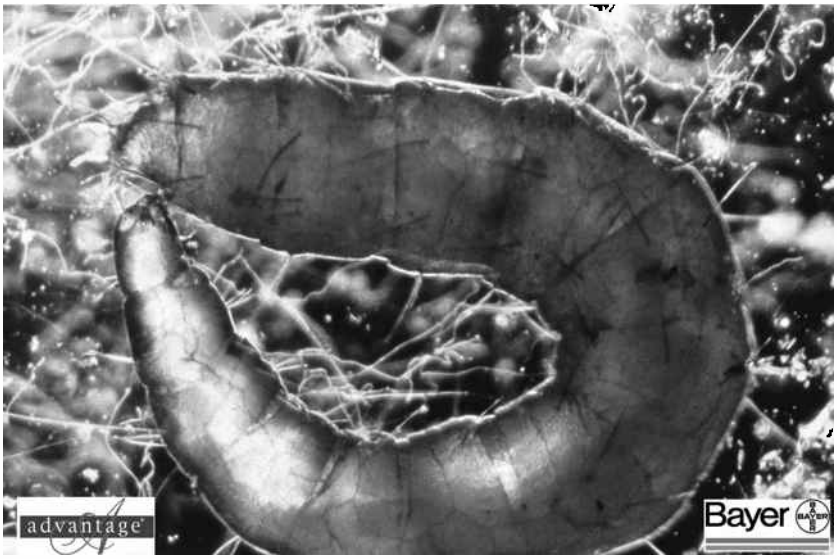

Fig. 6.2. A larval cat flea (*Ctenocephalides felis*) (Photo © Bayer).

housing they only represent about 5% of the total flea population, with pupae representing 10%, larvae 35% and eggs 50%.

Host Specificity

C. felis has been recorded infesting calves, lambs and kids maintained in barns on straw bedding, which is the ideal breeding site for fleas introduced by farm cats and dogs. Infestations are common to both sheep and goats, but incidence has been recorded to be higher in female goats (Yacob *et al.*, 2008).

The effects of host age on flea infestation are equivocal. In Ethiopia, Yacob *et al.* (2008) recorded that incidence was higher in young animals (particularly sheep). However, in Iran, it was observed that *C. felis* infestations increased with age, and older animals were more heavily infested (Yakhchali and Hosseine, 2006).

Finding a Host

The adult flea needs to detect a suitable host, orientate towards it and achieve contact. This is achieved through a number of host stimuli, the three most important being vibration, warmth and exhalation of carbon dioxide (Krämer and Mencke, 2001).

Feeding

Adult fleas are capillary feeders. Their mouthparts (maxillae) penetrate the host's skin and the tip of the labrum epipharynx enters a capillary. Saliva is passed into the host by means of a salivary pump and appears as clear droplets of fluid outside the capillary. The saliva contains anticoagulant, skin-softening and spreading agents, as well as low molecular weight material that can provoke an allergic response.

C. felis must feed every 12 h in order to reproduce and survive, and feeds to repletion in 10 min, imbibing 7 µl of blood and doubling its body weight. Female *C. felis* will start laying eggs within 48 h of the first feed. *C. felis* will feed more frequently at higher temperatures as a result of accelerated physiological activity and increased rate of water loss.

Pathogenicity

Heavy flea infestations can result in significant blood loss and severe anaemia, particularly in young sheep and goats (Kusiluka and Kambarage, 1996). Inflammation and pruritus may occur at the site of the bite, often leading to self-wounding to relieve the irritation. Death is not an uncommon outcome (Jain, 1993). A marked fall in the packed cell volume and haemoglobin concentration has been recorded, manifested clinically by pallor of the mucus membranes (Kusiluka and Kambarage, 1996).

Symptoms observed in rams have included depression, partial anorexia, debilitation, poor body condition and pale mucous membranes; death has been recorded in 10/25 (40%) of affected rams (Jain, 1993).

Prevention

Strategies to prevent the build-up of fleas in animal housing include the avoidance of overcrowding, and regular cleaning and changes of bedding (Kusiluka and Kambarage, 1996). Effective treatment of farm cats and dogs and prevention of their access to animal housing will also aid in preventing the build-up of fleas.

7

Diagnosis

Diagnosis of an ectoparasite infestation can be either direct or indirect. Direct diagnosis involves the isolation and identification of the causal ectoparasite. Indirect diagnosis involves detecting the presence of ectoparasite by-products (e.g. faeces) or specific antibodies produced by the host in response to exposure (serodiagnosis).

Differential diagnosis of ectoparasitic infestations of sheep and goats can be problematic as the general symptoms of all ectoparasites (Table 7.1) are more or less the same, and are also similar to a variety of non-parasitic skin infections. It must be borne in mind, however, that a sheep or goat may carry more than one ectoparasite (e.g. scab mites and lice), and possibly a non-parasitic skin infection, simultaneously. It is of paramount importance that the cause of flock/herd irritation is professionally identified. Administration of an inappropriate control strategy may require repeat treatment, which is costly and may select for ectoparasiticide resistance. A postal survey carried out by the Welsh Assembly Government (WAG) in 2006/7 highlighted that only 47.1% of respondent sheep farmers used veterinary surgeons for advice and diagnosis (Hybu Cig Cymru, 2007). The same postal survey data also highlighted that where veterinary surgeons examined flocks where the flock owner believed they had sheep scab (*Psoroptes ovis*), scab was only confirmed in 55% of cases (Hybu Cig Cymru, 2007). Thus, farmer identification of an ectoparasite problem can be unreliable and the administration of an appropriate treatment unlikely, making it even more difficult to eradicate a second time. In the case of permanent ectoparasites, all animals in the flock/herd should be considered to be infested and the whole flock should be treated (not just those presenting with clinical signs). One missed animal could reinfest the whole flock.

The direct diagnosis of an ectoparasite is not always easy. First, it is necessary to identify a sheep or goat potentially infested with an ectoparasite, based on the presence of clinical signs. Secondly, it is necessary to find an active lesion and, thirdly, it is necessary to isolate and identify the causative agent.

Clinical Signs

Sheep or goats infested with an ectoparasite may not present with the textbook clinical signs of infestation. For example, for the permanent ectoparasite *P. ovis* (the sheep scab mite) wool loss is not pathognomonic, and is not a reliable diagnostic tool. Dirty, greasy matted wool over the shoulders and brisket are far better indicators of scab (Bates, 2009a,b).

Table 7.1. Gross clinical signs of ectoparasitic infestation.

- General air of dejection
- Biting or licking of fleece leading to clean areas
- Dirty areas of fleece (particularly over withers) – through digging with hind feet
- Tags of fleece on flanks
- Tags of fleece in mouth
- Mild to excessive touch hypersensitivity response on manipulation
- Wool loss
- Wool grazing
- Scabby or scurfy lesions
- Aural haematomas or fibrosis

The subclinical phase of an ectoparasite infestation is the period between the animal contracting the parasite and presenting with obvious clinical signs. One of the obvious characteristics of subclinical ectoparasite infestations is that lesions are virtually undetectable, unless the animal is examined thoroughly. For the permanent ectoparasites, the sheep scab mite (*P. ovis*) and the chewing louse (*Bovicola ovis*), the subclinical phase can last 2–3 months, or even longer. For the semi-permanent ectoparasite *Lucilia sericata* (causing blowfly strike) the subclinical phase may last as little as 1–2 days. However, it is unlikely that there will be cause to investigate an animal with early subclinical infestations in which clinical signs are generally non-existent or mild and non-specific. Differential diagnosis can be problematic at this stage as these mild clinical signs are also indicators of the presence of non-parasitic skin conditions, as described later in this chapter.

In the case of sheep scab (*P. ovis*) veterinary intervention generally occurs once sheep are presenting with obvious visible clinical signs, when the infestation enters the rapid growth phase (Chapter 2). Unfortunately, this will be a long time after the initial introduction of *P. ovis* into the flock, when disease on the 'index case(s)' (i.e. the infested animal(s) introduced into the flock), and possibly on other susceptible contact sheep, enters the rapid growth phase (Bates, 2009a).

Locating a Lesion

Initially, the suspect sheep/goats should be observed 'over the farm gate' (trying not to be seen by the animals) noting any gross clinical ('visible') signs of possible ectoparasitic infestation (Table 7.1). Once an animal has been observed with suspicious clinical signs, it is then necessary to isolate this animal and locate the lesion. Locating a lesion is achieved through palpation of the skin with the tips of the fingers until a lesion (or 'warble') can be felt. Most mange mites (*Psoroptes*, *Sarcoptes* and *Chorioptes*) can produce a palpable scab lesion. However, other ectoparasites may not initiate a palpable lesion (e.g. chewing lice). Palpable lesions are most likely to be located where the fleece is damp, chewed or licked clean or dirty owing to scratching with the hind feet.

Sheep infested with scab mites (*P. ovis*) can also manifest an involuntary response (the touch hypersensitivity response, or THR, which can be scored; see Table 2.2) (Bates, 2009a). If a THR is elicited a lesion is likely to be in the vicinity of the skin palpation. However, field data has shown that over half (54.3%) of scab-infested sheep do not exhibit a response, thus the THR is not a reliable indicator of infestation (Bates, 2009a). Also, this involuntary response is a major clinical sign of scrapie. Infestations are generally well embedded in a flock at the point of veterinary involvement. Results of a study investigating the epidemiology of scab (*P. ovis*) within ten naturally infested sheep flocks in England and Wales showed that between 8% and 60% of sheep were infested at the point of veterinary intervention, with lesion areas ranging from 1.0 cm^2 to extensive body cover (Bates, 2009a).

Concentrating the lesion search on the predilection sites of possible ectoparasites and areas where there is wool/hair loss, tags

Table 7.2. Quality of skin scrapings submitted to the Veterinary Laboratories Agency (VLA) in the UK for sheep scab diagnosis (1986–1989).

	Quality of skin scrapings					
Year	Poor	Small	Fair	Good	Wool only	Total
1986	31	29	16	38	49	163
1987	14	36	32	75	29	186
1988	5	5	26	22	4	62
1989	5	6	4	11	2	28
Total	55	76	78	146	84	439
%	12.5	17.3	17.8	33.3	19.1	100

of wool/hair and/or obvious staining will often help to locate lesions quickly. Most (54.8%) sheep scab (*P. ovis*) lesions are located in an area from the neck to the mid-back and extending above the right and left forelegs (with the majority over the withers and mid-back) (Bates, 2009a). Scab mites and other mange mites do not travel very far from their initial point of contact and will generally initiate a lesion at this site, if conditions are suitable. Bates (2009a) has demonstrated that although the majority of sheep (51.1%) will present with a single discrete sheep scab lesion it is not uncommon for sheep to present with ten or more individual lesions. During the subclinical phase these lesions will be discrete, but as disease moves into the rapid growth phase many of these growing lesions will coalesce to form one large progressing lesion. Lesion areas at the point of veterinary intervention can therefore range from $<10\,cm^2$ to total body cover ($>4000\,cm^2$) in 29% and 4% of sheep examined, respectively (Bates, 2009a).

Chewing lice of sheep and goats (*Bovicola* spp.) do not produce a definite lesion and will therefore only be accidentally found using the skin palpation technique for sheep scab and mange. If lice are suspected it is necessary to examine sheep/goats specifically for them. To do this select at least ten sheep/goats and examine each by parting approximately 10 cm of wool/hair to skin level; make at least ten partings per side of the animal and estimate the numbers of lice seen. If no lice are seen, examine another ten animals or reinspect the flock/herd in 3–4 weeks. Even adult lice are relatively small and very mobile and can easily move in and out of your focal plane. The distribution of *B. ovis* is uneven; the lice can be found in high numbers in localized colonies and can be missed if the fleece/hair is only parted in one or two places. If 10% of a flock/herd is infested, the selection of only one animal at random will give only a one-in-ten chance of selecting an infested animal (Joshua, 2001).

In early louse (*B. ovis*) infestation, only a few sheep will be infested. Visual inspection is not always reliable if sheep are louse free. Lice in small numbers are difficult to find – at least 400–500 lice must be present before an infestation can be detected by inspection on unshorn sheep. If a sheep has 100 lice, equivalent to 0.5 lice per parting, inspection over 20 partings will only give a 60% chance of finding lice on this animal (Joshua, 2001). In light infestations on sheep with less than 6 months' wool growth, lousy sheep may be impossible to identify and lice difficult to find. Medium-to-heavy infestations are easier to detect.

Lice increase at a greater rate on sheep that have a low immune system, are in poor condition or are affected by disease. These can be targeted when inspecting for the presence of lice in a flock (Joshua, 2001). Target sheep presenting with signs of wool derangement and poor condition. Sheep can start rubbing with as little as 100 lice, therefore selecting a rubbing sheep also greatly improves the chances of finding an infested animal. Inspections for lice can be carried out at any time that sheep are gathered, especially at crutching or shearing. In merinos,

it is necessary to pay particular attention to neck folds and longer wool on the neck. In woolly sheep, inspect anywhere along the sides, neck, back or rump (Joshua, 2001).

Isolating the Causative Agent

Once a lesion is located it must be examined for the causative ectoparasite. Mange mites such as sheep scab mites (*P. ovis*) are not always visible to the naked eye and are hard to detect *in situ*. The majority of sheep scab lesions will present with either no mites (27.3%) or less than ten adult female mites per lesion (52.0%) (Bates, 2009a). In most cases mites are located around the moist edge of the lesion, with the greatest numbers found at the lesion edge at the lowest point down the flanks (owing to the natural motion of skin lipid with gravity) or at the lesion edge over the backbone, furthest away from the head (Bates, 2009a). If the lesion covers the entire body and no leading edge is apparent, the scab may be in the regressive phase of infestation. Under these circumstances, examination of the cryptic sites (ears, external ear canal, infra-orbital fossae, interdigital fossae, inguinal fossae, crutch and perineum) may reveal mites *in situ* (Bates, 2009a). In the majority of cases of suspected sheep scab and other forms of mange it is necessary to take a skin scraping for effective diagnosis.

Skin scraping

A positive diagnosis of mange in small ruminants requires the isolation and identification of the infesting ectoparasite. Visual examination of lesions may reveal the larger permanent ectoparasites (e.g. *Psoroptes* and *Bovicola*) and semi-permanent ectoparasites (ticks and fly larvae), but in most cases it is necessary to take skin scrapings from the edge of visible lesions. In diagnosing mange (scabies) it must be borne in mind that the distribution of wool/hair loss or derangement and/or staining can bear no relation to the location of the lesion. These clinical signs are more than likely in areas where the sheep or goat can effectively rub or scratch, but lesions may be located in more inaccessible areas.

The area selected for scraping depends on the ectoparasite. For *P. ovis*, the scraping should be taken from the moist part or the edge of the lesion. For other forms of mange, random areas of the lesion itself should be taken. The wool/hair over the sample area should be clipped as close to skin level as possible and stored in a paper envelope for the differential diagnosis of mycotic dermatitis, fleece rot and other bacterial or fungal infections; storage of the wool/hair sample in a plastic bag will result in a build-up of excess moisture and will affect effective differential diagnosis for non-parasitic infections. Scrapings destined for ectoparasite examination should be stored in a sealed, transparent, plastic bag until examination. Scrapings can be stored at +4°C for a few days without affecting the viability of the ectoparasites. The wool/hair sample can also be analysed for acaricide/insecticide concentrations to confirm effective treatment and can be frozen (at below –20°C) until required. Lice or fly larvae may also be located in this wool/hair sample, which should therefore be examined should the skin scraping be shown to be negative for ectoparasites.

Ideally, scrapings for sheep scab (*P. ovis*) diagnosis should be taken at the interface between lesion and unaffected skin, but this may not be possible if the lesion has covered the entire body. Small lesions can be scraped in their entirety but larger lesions need to be scraped at several sites around the leading edge and the scrapings pooled together. If sarcoptic mange is suspected, the scraping should be taken from the hairless area or where pruritus or pimples are seen. In general, for mites living on the skin surface (i.e. *Psoroptes* or *Chorioptes*) scrapings should be taken with the scalpel blade held at an acute angle, shaving rather than scraping off the outer epidermis. However, *Demodex*, *Psorobia* or *Sarcoptes* mites are found burrowing into the skin and the scalpel blade should be held at right angles and the skin scraped until it oozes blood.

Effective diagnosis is directly related to the quality of the skin scraping. Between 1986 and 1989 the Veterinary Laboratories Agency (VLA), in England and Wales was asked to record the quality of the skin scrapings received for sheep scab (*P. ovis*) confirmation. Quality was subjectively scored according to the relative amounts of scab material available for examination as: (i) wool only (no scab material); (ii) poor (inadequate amounts of scab material); (iii) small (small amounts of scab material); (iv) fair (adequate amounts of scab material); or (v) good (large amounts of scab material). In total, the quality of 439 skin scrapings was assessed (Table 7.2). Overall, only 51.1% of scrapings were considered adequate for an effective diagnosis of scab, of which 17.8% were fair and 33.3% good; 17.3% of scrapings were scored as small. However, it is appreciated that in a lot of cases, particularly when the scab lesion is in the subclinical phase, there is minimal material to scrape. The remaining 31.6% of scrapings were totally inadequate for an effective sheep scab diagnosis: 12.5% scored as poor and 19.1% as wool only (Bates, 2009b).

A drop of glycerine or liquid paraffin put on the skin or scalpel blade before the skin is scraped can aid in the collection of mites (Smith, 1988). In pustular demodectic mange, mites are usually abundant and can be demonstrated on examination of the cheesy contents of an expressed or incised pustule. In the case of squamous lesions, a deep scraping may be necessary.

In cases of ear mange, the scabby material within the external ear may be detached with blunt-ended forceps. Skin scrapings should be immediately transferred into small tubes that can be securely stoppered or into 'self sealing', transparent, plastic bags. Live *Chorioptes*, *Psoroptes* and *Sarcoptes* can easily be seen through direct examination of the original skin scraping or ear swab through the unopened tube or bag under a dissecting microscope (×40) with overhead lighting. Mites will be active after incubation of the sample at 37°C for 30 min and can easily be transferred to microscope slides using a mounted needle or camel hair brush.

Ectoparasites can be mounted in either Berlese's fluid (gum chloral), Vitzhum's fluid, Hoyer's medium or Heinze's modified PVA medium (Evans, 1992). A drop of the mounting medium is placed in the centre of a microscope slide and the specimen transferred into it by means of a fine brush or mounted needle; air bubbles are removed with a needle. The coverslip is placed on its edge to the side of the medium and slowly lowered using a needle, then pressed gently with the needle. If there is too much medium the pressure will force some of it out. If there is too little medium, small drops of fresh medium can be added, a little at a time, letting it flow under the coverslip. After mounting, slides should dry at room temperature for 5–7 days before ringing with nail polish or another non-soluble sealant. The drying time can be decreased by placing the slides in an oven (at 40–45°C) for at least 2 days. Berlese's fluid and other mounting mediums will also slowly 'clear' the specimens, digesting away non-chitinous body material, and rendering the parasite easier to identify.

Potassium hydroxide digestion

To locate dead mites or lice, the scraping needs to be processed in hot potassium hydroxide (KOH). Large amounts of material (up to 5.0 g) can be placed in a glass boiling tube and covered with 10% KOH. The tube is then placed in a beaker of water, which is gradually brought to the boil. After boiling for 5–10 min, the digest is allowed to cool and then centrifuged at 600 ***g*** (2000 rpm) for 10 min. Prolonged boiling should be avoided as mites may eventually disintegrate. Faster centrifugation may be required for smaller species (e.g. *Demodex*). The supernatant is quickly decanted and the deposit examined microscopically (Fig. 7.1). Alternatively, small numbers of specimens can be placed in lactic acid on a glass cavity (indented) slide. The slide is then passed constantly over a Bunsen burner or spirit lamp flame. Care must be taken that it does not get too hot, as escaping body gases in the mite may cause the mites to 'jump'. If smoke appears on the surface of the fluid,

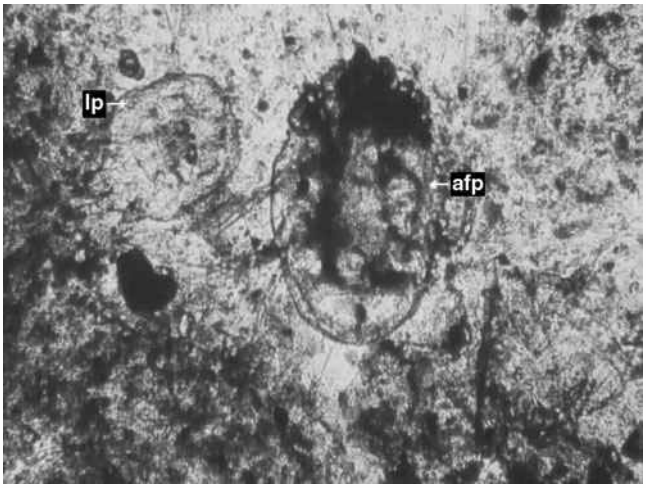

Fig. 7.1. Microscopical examination of skin scraping sediment following potassium hydroxide (KOH) digestion (afp, adult female *Psoroptes ovis*; lp, larval *Psoroptes*) (Photo © P. Bates).

the process is too hot. These methods are necessary to clear out the opaque body contents in order to prepare the mites for microscopical examination. It is advisable to carry out both these methods in a cabinet with an extractor fan because of the caustic fumes that are released.

KOH digestion can only confirm the presence of dead ectoparasites. Information on whether the ectoparasites are alive or dead may be essential in a successful prosecution. Live ectoparasites indicate an active infestation and, therefore, that it has possibly not been treated. Dead ectoparasites suggest that the infestation has been treated or that the ectoparasites may have died sometime between taking the scraping and examination at the diagnostic laboratory. It is, then, important that skin scrapings are submitted to the diagnostic laboratory as quickly as possible and that the scrapings are examined as soon as possible after receipt.

Examination of skin scrapings should be carried out by trained and experienced staff. Scrapings may only harbour one mite or louse and skill is required in locating and identifying this ectoparasite. Sheep or goats may also carry more than one ectoparasite (e.g. scab mites and lice) simultaneously. If relatively large chewing lice are identified by direct microscopical examination, the presence of a small number of scab mites should not be ruled out.

Ear swabbing

In suspect cases of otoacariasis (*Psoroptes* or *Raillietia*) live mites can be observed through examination of the external auditory canal (EAC) using an auroscope, but this technique may be difficult if applied to larger animals or large numbers of animals. For effective diagnosis of otoacariasis, it is necessary to swab the EAC (Bates, 1996a,b). Suitable sized swabs are inserted into the EAC until resistance is met, then gently twisted and removed. Care must be taken that the swabs enter the EAC and not the blind pouches of the tragus. Care should also be taken with young animals.

Swabs should be immediately transferred into small tubes that can be securely stoppered. Live *Psoroptes* or *Raillietia* can easily be seen during direct examination of the original ear swab under a dissecting microscope (×40) with overhead lighting. As for skin scrapings, mites will be active after incubation of the swab at 37°C for 30 min and can easily be transferred to

microscope slides for identification using a mounted needle. Mites can also be mounted as described for skin scrapings. To locate dead mites, swabs can be processed in hot KOH, again as for skin scrapings.

Differential Diagnosis and Mixed Infections

Sheep can be infested with a number of ectoparasites and/or non-parasitic skin conditions, and the clinical signs of the latter may be easily confused with those of an ectoparasitic infestation, particularly a subclinical infestation.

Non-parasitic skin conditions

Non-parasitic skin conditions can be classified as hereditary/congenital, as the result of prion, viral, bacterial or fungal infections, or as allergic responses to non-parasitic arthropods or plant matter. In particular, it is sometimes difficult to differentiate between sheep scab mite (*P. ovis*) infestation and advanced cases of scrapie. It has been demonstrated that 15% of farmers responding to a postal survey indicated that they would dip or inject sheep as a method of scrapie control (Hybu Cig Cymru, 2007), suggesting that there was confusion between scrapie and sheep ectoparasites, particularly sheep scab. The possibility of confusion was supported by the fact that more farmers from scrapie-affected farms thought the disease was sheep scab (Hybu Cig Cymru, 2007).

Non-parasitic skin conditions (Michell, 1988, 1990; Sargison, 1995) include the following:

- *Hereditary/congenital*: 'red foot'.
- *Prion*: scrapie.
- *Viral*: border disease ('hairy shakers', congenital trembles); contagious pustular dermatitis (orf, contagious ecthyma, 'scabby mouth'); foot-and mouth-disease.
- *Bacterial*: actinobacillosis ('cruels', 'kings evil') caused by *Actinobacillus lignieresii*; clostridial infections (malignant oedema, 'big head' of rams) caused by *Clostridium chavoei*, *Clostridium oedematiens*, *Clostridium perfringens*, *Clostridium septicum* or *Clostridium sordellii*; fleece rot ('canary stain') caused by *Pseudomonas aeruginosa*; staphylococcal folliculitis ('plukey lambs') caused by *Staphylococcus aureus*; staphylococcal dermatitis (facial eczema, periorbital eczema, 'eye scab') also caused by *S. aureus*; scald (benign footrot) caused by *Bacteroides nodosus* or *Fusibacterium necrophorum*.
- *Fungal*: mycotic dermatitis ('dermo', actinomycotic dermatitis, dermatophilosis, 'lumpy wool', 'strawberry footrot') caused by *Dermatophilus congolensis*; or ringworm caused by *Trichophyton verrucosum*.
- *Allergic reactions*: Fly bite dermatitis caused by *Culicoides* spp.; photosensitization ('yellows', 'plochteacht', 'alveld') caused by *Hypericum perforatum* (St John's wort) or *Narthecium ossifragum* (bog asphodel).
- *Other*: wool slip ('alopecia'), skin tumours or sunburn.

Sheep ectoparasitic conditions

The current relative prevalences of some sheep ectoparasitic infestations and other skin diseases in the UK are shown in Table 7.3.

During the UK Sheep Scab Eradication Campaign 1974–1992 it was a requirement for all sheep suspected of having scab to be examined by a veterinary officer and for skin scrapings to be taken from these suspect sheep and submitted to the Central Veterinary Laboratory (CVL, later the VLA, at Weybridge) for confirmation of the presence (or absence) of *P. ovis*. During the 16 year period between 1976 and 1992, some 138 scrapings taken from sheep suspected of having sheep scab were shown to contain ectoparasites other than *P. ovis* (Table 7.4). A small number of these were mixed infestations with *P. ovis* (Bates, 2009b). The most frequent

Table 7.3. Prevalence of sheep ectoparasite infestations and other diseases in the UK, 2000–2007 (Source: Veterinary Investigation Data Analysis (VIDA) returns, 2000–2007).

Skin infestation/disease	Number of positive submissions/year							
	2000	2001	2002	2003	2004	2005	2006	2007
Sheep scab	365	217	192	224	279	250	190	231
Lice	NR[a]	NR	1	8	65	67	80	100
Blowfly	16	4	7	4	14	5	18	15
Keds	0	0	0	0	1	0	1	0
Dermatophilus	21	16	16	6	15	12	5	19
Ringworm	28	15	8	19	14	6	4	4
Orf	54	28	30	39	35	27	40	43
Periorbital eczema	18	8	8	7	6	9	6	2

[a]NR, Not recorded.

Table 7.4. Ectoparasites other than *Psoroptes ovis* in skin scrapings submitted during the UK Sheep Scab Eradication Campaign 1976–1992.

	Chorioptes	Forage mites	Blowfly larvae	Lice
Total	2	33	92	10[a]
%	1.5	23.9	66.7	7.2

[a]Including one identification of blood-sucking *Linognathus* spp.

ectoparasites identified were blowfly larvae (66.7%), followed by forage mites (23.9%) and lice (7.2%). *Chorioptes bovis* and small biting flies (possibly *Culicoides* spp.) were identified on a small number of occasions (1.5% and 0.7%, respectively). Blowfly larvae, forage mites, *C. bovis* and biting flies were found only after KOH digestion of the skin scraping and were therefore very unlikely to have been observed by the naked eye. The majority of lice were live, and identified by direct microscopical examination of the skin scraping.

Sheep infested with these ectoparasites obviously presented with clinical signs that could have been confused with sheep scab. The years of compulsory plunge dipping for the eradication of sheep scab had significantly reduced the prevalence of other ectoparasites. However, since the deregulation of sheep scab as a notifiable disease in 1992, all sheep ectoparasites are now widespread within the UK national flock, thus confusing the differential diagnosis of sheep scab.

Blowfly larvae detected in skin scrapings are generally identified after KOH digestion and are usually first-instar (L_1) larvae, suggesting that they were from young lesions that had been either cured or had died out before the examination of the sheep for scab. In one case, blowfly larvae were identified exclusively on one scraping out of six, and the remaining five scrapings were infested with live *P. ovis*. In another case, a sheep presented with a mixed infestation of blowfly strike and *P. ovis* – both identified after KOH digestion (Bates, 2009b).

Forage mites are found in skin scrapings throughout the year, but are generally a problem in housed sheep. Mites in the genera *Acarus* or *Tyrophagus* can occur in very large numbers in hay and straw bales, often increasing to extremely large numbers over the autumn.

The clinical signs of chewing lice can be confused with those of sheep scab, so that possible resistance may occur in both ectoparasites if they are not professionally identified and the correct treatment applied. The two ectoparasites can be found in a flock simultaneously. Field investigations have identified flocks in which sheep are either exclusively infested with either lice or scab mites. However, sheep can present with mixed infestations of *P. ovis* and lice. Studies at the VLA have shown that sheep

with a predisposing infestation of chewing lice (*B. ovis*) may not accept challenges by sheep scab mites, whereas sheep with active scab can be colonized by lice following natural exposure (Bates, 2009a). The exact nature of this inter-species exclusion is unknown, but the skin changes initiated by lice feeding/excretion may render it unfavourable for mite colonization. Lice, in contrast, may actively feed on the scab lesion.

Zoonoses

Potential zoonotic problems may occur when handling infested animals or diagnostic material containing *Sarcoptes* or *Notoedres*. Faeces or cuticular debris from any mite species may be a hazard to those prone to house dust mite (*Dermatophagoides pteronyssinus*) allergy. Also, the risk of ringworm (*Trichophyton verrucosum*) infection should be considered when handling wool or hair samples.

Identification of Ectoparasites

It is not within the scope of this book to provide detailed information on the identification of the possible insect, mite or tick species found on sheep or goats. Specialist illustrated keys should be consulted in order to identify the causative organism. Suitable keys for the identification of mites and ticks are described in Baker (1999) and for myiasis fly species in Zumpt (1965) and Erzinçlioğlu (1996). However, a section on the identification of blowfly larve is included below.

Identification of blowfly larvae

Anatomical features of taxonomic value found on the larvae of the myiasis causing fly species include the structure of the cephalopharyngeal skeleton ('mouthparts'), the structure of the posterior spiracles and the presence and shape of denticles, spines or scales on the integument (skin) (Zumpt, 1965).

The cephalo-pharyngeal skeleton (Fig. 7.2), the internal skeleton of the anterior ('pointed') end of the larva, is often visible through the translucent integument, or can be seen by clearing (in Berlese's fluid) and mounting the larva (or specifically its anterior segments) on to a microscope slide. The externally projecting parts are the 'mouth hooks' (labial sclerites). In some groups (e.g. the *Calliphora*) an accessory sclerite is situated under the mouth hooks. The paired pharyngeal sclerites are usually large and extend posteriorly into a dorsal or ventral horn (Zumpt, 1965). The structure of the cephalo-pharyngeal skeleton can be used to differentiate *Lucilia* from *Calliphora*. In *Calliphora*, the oral sclerite is wholly black, whereas in *Lucilia* it is colourless (with the exception of *Lucilia ampullacea*, in which the hindmost tip is black or brown) (Erzinçlioğlu, 1996).

The posterior spiracles (Fig. 7.3) are found at the posterior ('wide') end of the larva. In first-instar (L_1) larvae they normally consist of two pairs of simple, circular or oval holes. In the second- (L_2) and third-instar (L_3) larvae two or three pairs of slits are present, respectively (Zumpt, 1965). In *L. sericata*, L_1 larvae possess one slit, L_2 larvae two slits and L_3 larvae three slits (Erzinçlioğlu, 1996). Usually the slits are surrounded by a strongly sclerotized open or complete ring (the peritreme) or they lie in a sclerotized plate (e.g. the pores in the Oestridae). In a ventral or lateral position,

Fig. 7.2. Light microscope image of the anterior region of *Lucilia sericata* showing the cephalopharyngeal skeleton (Photo © P. Bates).

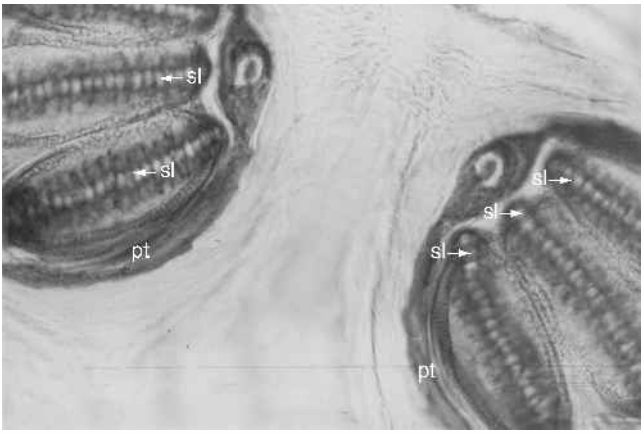

Fig. 7.3. Light microscope image of the posterior spiracles of *Lucilia sericata* (pt, peritreme; sl, slit) (Photo © P. Bates).

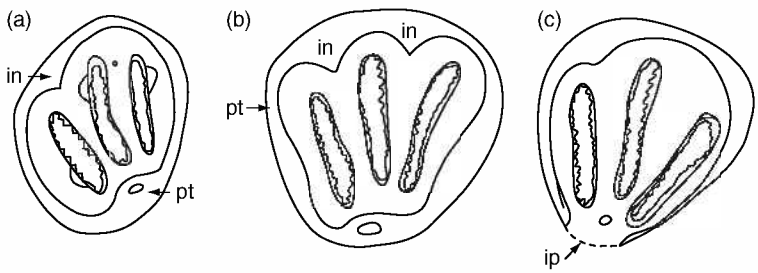

Fig. 7.4. Diagram of the posterior spiracles of third-instar (L_3) blowfly larvae. (a) *Lucilia* spp.; (b) *Calliphora* spp.; and (c) *Wohlfahrtia/Sarcophaga* spp. (in, indent; ip, incomplete peritreme; pt, peritreme).

a rounded structure (the 'button') often occurs (Zumpt, 1965). Fly genera in which the peritreme is complete (closed) include *Calliphora* and *Lucilia*. In *Lucilia*, there is a single indentation of the peritreme, whereas in *Calliphora* there are two indentations (Fig. 7.4). Fly genera where the peritreme is incomplete (open) include *Sarcophaga*, *Wohlfahrtia*, *Chrysomya*, *Phormia* and *Cochliomyia* (Fig. 7.4). In *Sarcophaga* and *Wohlfahrtia* the posterior spiracles are situated in a cavity.

The larval integument ('skin') is rarely bare, and is at least partly covered with denticles, spines or scales (Fig. 7.5), which are often arranged in circular, more or less complete belts (Zumpt, 1965). In *Calliphora vomitoria* the spines have rounded tips, in *Calliphora vicina* and other *Calliphora* spp. the spines are smaller and with pointed tips (Erzinçlioğlu,1996).

Age Determination of Blowfly Lesions

Growth rates of sheep blowfly (*L. sericata*) larvae have been determined at temperatures between 8 and 40°C. Where the temperature of the sheep is roughly constant, a growth curve ('isomegalendiagram') can be used for ageing the lesion, deduced from the length of the larvae (Smith, 1986; Rankin and Bates, 1998). Isomegalendiagrams have been produced to provide a scientific basis for the age estimation of *L. sericata* found on sheep in animal welfare cases. If the sheep body temperature, strike lesion temperature and ambient temperature are known, larvae

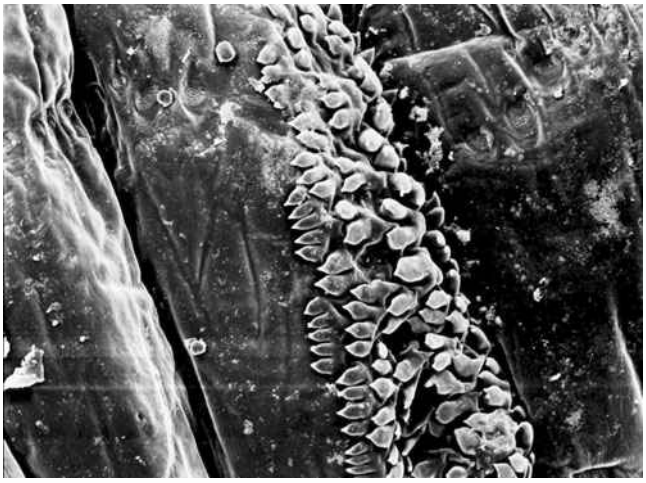

Fig. 7.5. Scanning electron microscope image of the cuticle of *Lucilia sericata* showing the cuticular denticles (Photo © P. Bates).

may be identified and their approximate age extrapolated from the graph, as well as identifying secondary strike lesions by the presence of multiple larval stages. It is very important that the larvae are submitted for ageing in a standard manner, and that all parameters – such as temperatures – are recorded in detail. Estimation of the age of lesions using plasma ammonia or urea nitrogen levels has also been investigated (Groves and Bates, 1998; Groves, unpublished data), but at present have been shown to be unreliable.

Serodiagnosis

Direct diagnosis is based on the identification of infested sheep/goats (based on clinical signs), location of an active lesion (through animal examination and skin palpation), and isolation and identification of the causative ectoparasite (through the microscopical examination of skin scrapings – and of ear swabs). These traditional methods of diagnosis have been the standard techniques for two UK sheep scab eradication campaigns (1928–1953 and 1974–1992), and for *The Sheep Scab Order 1997* (the current UK sheep scab legislation).

Sensitivity and specificity of skin scraping

Clinical signs of ectoparasite infestation are not always presented (particularly in the subclinical phase) and examination of skin scrapings using microscopical techniques exhibits only low-to-medium sensitivity (Meleney and Christy, 1978); the diagnosis of ectoparasites, particularly sheep scab (*P. ovis*) based on traditional methods can be therefore be unsatisfactory. Ochs *et al.* (2001) demonstrated that, depending on the occurrence and severity of clinical signs of sheep scab, the diagnostic sensitivity of skin scrapings can range between 18.2% and 66.7%, distinctly lower than seropositivity recorded by ELISA, which varies between 54.5% and 100%. In addition, taking skin scrapings can be time-consuming in locating subclinical lesions to sample and can be inadequate for diagnosis when small numbers of mites are present (Meleney and Christy, 1978; National Research Council, 1979). The quality of the scraping is also directly related to the experience of the operator (Bates, 2009a). The cryptic sites (EAC, infra-orbital fossae and inguinal fossae) also have to be examined for live mites, thus increasing the examination time. The development of immunoassays for sheep scab mites (*P. ovis*) can provide an alternative

method for detecting small numbers of mites (Fisher, 1983; Fisher *et al.*, 1986; Wassall *et al.*, 1987) and infestations in the subclinical phase. A serodiagnostic technique for detecting ectoparasite-specific antibodies in the blood would be more cost-effective in assessing flocks for permanent ectoparasites (e.g. sheep scab mites) than the physical examination of individual sheep and the taking and examination of skin scrapings from sheep presenting with clinical signs. Thus, more sheep can be sampled for serodiagnosis than are sampled in traditional methods.

Enzyme-linked immunosorbent assay (ELISA)

ELISA is one of the commonest test systems employed in serodiagnosis, particularly for the serodiagnosis of ectoparasites. Serosurveillance using an ELISA method was integral in the eradication of bovine warble fly (*Hypoderma bovis* and *Hypoderma lineatum*) from the UK (Webster, 1998), and an ELISA method is currently being utilized in the porcine sarcoptic mange (caused by *Sarcoptes scabiei* var. *suis*) eradication campaign in the Netherlands (Rambags, 2001). ELISA methods have also been investigated for the serodiagnosis of ectoparasite infestations of small ruminants, namely the sheep scab mite (*P. ovis*), sheep chewing louse (*B. ovis*), nasal bot fly (*Oestrus ovis*) larvae and goat warble (*Przhevalskiana silenus*) larvae.

When discussing serodiagnostic methods, two terms regularly used are sensitivity and specificity. High sensitivity equates to a test that produces very few false positives, high specificity equates to a test that produces very few false negative results. In a given test system, the two parameters are linked, so that if the cut-off between positive and negative results is adjusted to increase the sensitivity, the specificity falls. These two topics are discussed later in this section on serodiagnosis.

Psoroptic mange (sheep scab)

Antibody responses to *Psoroptes* spp. infestations have been documented in domestic and wildlife hosts (deVos *et al.*, 1980; Boyce and Brown, 1991; Boyce *et al.*, 1991a,b), and two serological methods, immunoblotting and ELISA, have been researched for use in the serodiagnosis of sheep scab. Scab lesions presenting with live mites have been shown to be seropositive by both immunoblotting and ELISA (Grogono-Thomas *et al.*, 1989) using *P. ovis* extracts as antigen (Jayawardena *et al.*, 1988). Immunoblotting appeared to be more sensitive: whereas 5/5 (100%) lambs presenting with signs of early sheep scab were positive by immunoblotting, only 1/5 (20%) of the same lambs were positive by the ELISA method tested.

Immunoblotting, particularly the staining of antigens in the 12–34 kDa range has been successfully used for the diagnosis of subclinical scab in bighorn sheep (*Ovis canadensis*). When mite numbers were relatively low (Boyce *et al.*, 1991a) the method consistently recognized *Psoroptes* antigens in the 12–34 kDa range in infested sheep, whereas serum from non-infested bighorn sheep reacted weakly, if at all, with a small number of antigens in the 34–164 kDa range (Boyce *et al.*, 1991a). However, immunoblotting is a primarily qualitative technique, and a quantitative relationship could not be established between the severity of infestation and the numbers of antigen-antibody bands (Boyce *et al.*, 1991a). Notwithstanding, antibody responses to the 12–34 kDa antigens proved to be a sensitive indicator of *Psoroptes* sp. infestation in affected animals, including four asymptomatic bighorn sheep where fewer than ten mites were recovered (Boyce *et al.*, 1991a).

Although immunoblotting appears to be the more sensitive technique, ELISA is the more robust and time-effective method. A kinetic ELISA, developed using antigenic abstracts prepared from *Psoroptes cuniculi* mites, has been shown to be highly reproducible and accurate with sensitivities and specificities of 100% and 97.7%, 94.6% and 97.7% and 94.6% and 100%, respectively (Boyce *et al.*, 1991b). An improved ELISA developed by the University of Zurich in Switzerland demonstrated diagnostic sensitivity of 93.7% in 191 sheep with clinical scab originating from 29 flocks where *P. ovis* mites were detected by clinical examination.

In another study, 49% of 70 clinically uninfested sheep originating from infested flocks were also seropositive, suggesting that asymptomatic subclinical infestations can be diagnosed serologically. Specificity was 96.5% as determined with 254 sheep originating from 44 flocks without clinical mange (Ochs *et al.*, 2001).

ELISA specificity

It is important that a serodiagnostic method is able to detect infestations in the subclinical phase of disease. ELISA studies using *P. ovis* passaged on calves demonstrated that antibody titres to *P. ovis* were detectable as early as 30 days post-infestation, when lesions ranged from 1.0 to 50 cm^2 in area; but the antibody titre rose dramatically after this time and was easily detected as the lesion itself spread – coinciding with the rapid growth phase, when clinical signs were more obvious (Bates, 1997a). However, studies in Switzerland and Scotland have demonstrated that scab can be detected 2 weeks after challenge (Ochs *et al.*, 2001; van den Broek *et al.*, 2003) and 2 weeks before clinical signs become obvious (Ochs *et al.*, 2001).

Diagnostic specificity may be related to lesion size, with fewer false negatives as the lesion progresses. The Zurich ELISA detected 1.5% of lesions <10 cm^2 (<0.2% body cover, BC), 33% of lesions between 10 and 50 cm^2 (0.2–1.0% BC), 80% of lesions between 50 and 100 cm^2 (1.0–2.0% BC) and 100% of lesions >100 cm^2 (>2.0% BC) (Bates *et al.*, 2007c). Further extended studies, using a larger number of sera, confirmed that specificity was increased to 4% for lesions <1.0 cm^2, 23% for lesions between 1.0 and 10.0 cm^2, 30.5% of lesions between 10.0 and 25.0 cm^2, 93.8% of lesions between 25 and 50 cm^2, and 100% of lesions >50 cm^2 (Bates, Schnyder, Rankin, Grimm and Deplazes, unpublished (in preparation)). This specificity increases with lesion size and, therefore, with time as the lesion progresses.

One of the requirements of the UK Sheep Scab Eradication Campaign (1974–1992) was the compulsory examination of all sheep suspected of *Psoroptes* spp. infestation by a Government Veterinary Officer. Suspicion was based on clinical signs and confirmation of infestation was through the identification of *Psoroptes* (live or dead) in skin scrapings. Veterinary Officers were trained in the correct method of taking skin scrapings. In addition, from 1986 onwards Veterinary Officers were also asked to voluntarily submit a blood sample from the animal concerned along with the skin scrapings. ELISA results were then compared with those of the microscopical examinations of the corresponding skin scrapings (Bates *et al.*, 2009). Scab mites (*P. ovis*) were confirmed in 49.8% of the submitted skin scrapings, with 98.6% also confirmed positive by the Improved ELISA. This diagnostic specificity was comparable to the 93.7% recorded by Ochs *et al.* (2001) using the same ELISA method. However, an anomaly was observed whereby 1.4% (2/148) of skin scrapings with live *P. ovis* observed *in situ* were seronegative by ELISA (i.e. gave a false negative).

ELISA sensitivity

An ELISA designed to detect *P. ovis* antibody must have a high sensitivity, with few false positives. Sheep can be infested with a number of ectoparasites other than *P. ovis* and there is a possibility that these other ectoparasites may immunologically cross-react, becoming false positives. Sera from sheep infected with *P. ovis* have shown cross-reactivity to crude antigen extracts from *S. scabiei* var. *suis*, *Notoedres cati* and *C. bovis* (Matthes *et al.*, 1996). Cross-reactivity in a low range has also been detected in sheep infested with forage mites (*Tyrophagus*, *Glycyphagus* and *Acarus*) and *C. bovis* (Ochs *et al.*, 2001; Falconi *et al.* 2002). No cross-reactivity has been observed in keds (*Melophagus ovinus*), the tick *Dermacentor marginatus* (Ochs *et al.*, 2001), blowflies (*Lucilia* spp.), chewing lice (*B. ovis*) or the tick *Ixodes ricinus* (Wassall *et al.*, 1987). There was also no apparent cross-reactivity in the helminths *Fasciola hepatica*, *Nematodirus battus* and *Ostertagia circumcincta*, or *Dermatophilus congolensis* (the causative organism of mycotic dermatitis) (Wassall *et al.*, 1987).

The Improved ELISA has been shown to be 57% effective in detecting *P. cuniculi* in the EAC compared with ear swabbing (42%) and clinical signs (17%) (Bates *et al.*, 2007b). Bates *et al.* (2009) also demonstrated that only 54.4% scab cases confirmed negative through microscopical examination of skin scrapings were also confirmed negative by the Improved ELISA. This sensitivity was relatively low compared with the published values of 96.5% (Ochs *et al.*, 2001) and 100% (Bates *et al.*, 2007c), and a value of 97.6% measured by Bates, Schnyder, Rankin, Grimm and Deplazes (unpublished) for the Improved ELISA.

Residual antibody

A fundamental problem with a serodiagnostic method is the inability to differentiate between active or treated infestations, as the ELISA may be detecting residual anti-*P. ovis* IgG from a previously treated infestation. In sheep, anti-*P. ovis* antibodies have been recorded to decline slowly after treatment with the macrocyclic lactone (ML), doramectin, but remain positive in 50% of sheep beyond 17 weeks (Ochs *et al.*, 2001). Anti-*P. ovis* antibodies can be detected for a long period of time following treatment, the duration of which is related to the size of the lesion at the point of treatment. Antibodies can remain residual for 254 days for lesions of 4203 cm^2, 84 days for lesions of 252 cm^2 and 21 days for lesions of 130 cm^2 (Bates *et al.*, 2009).

Lesions, clinical signs and pruritus can resolve considerably quicker in dipped sheep than in those treated with the ML ivermectin (Bates and Groves, 1991), presumably because dipping also washes out *P. ovis* antigen from the lesion. The antibody titre appears to decrease as the dead scab material is carried away from the skin as the fleece grows. It would, therefore, be expected that antibody titres would take longer to decline in sheep treated with an ML than in those treated by plunge dipping.

A national survey for scab using a validated ELISA technique will help to identify geographical areas where scab is 'embedded', and thus strategically direct resources to these areas if an eradication campaign is in operation. A national survey similar to this, using the Improved Zurich ELISA, has been carried out for scab in Switzerland, where it was estimated that 15% of the national flock was seropositive for *P. ovis*. Prevalence using 16,404 sera was 10.4%, and 11.9% of the 2083 flocks were diagnosed as positive (Falconi *et al.*, 2002). This was significantly higher than the 0.3% determined from the number of annual outbreaks notified. Additionally, there was a significant increase found for mean seropositivity relative to flock size ($P<0.001$, linear regression); larger flocks had a higher risk of sheep scab (Falconi *et al.*, 2002). However, it is likely that a number of ELISA-positive sheep had residual anti-*P. ovis* IgG following previous treatment, so the figure of 15% that had been estimated may not have been for active scab.

Similarly, a validated ELISA for sheep scab could be used in disease eradication campaigns in clearly defined geographical areas, as was carried out by Jacober *et al.* (2006) for the eradication of scab from Canton Schwyz, again in Switzerland. All the flocks in the canton were serologically tested using the Improved Zurich ELISA in 2001 and 2002 (587 and 565 flocks, respectively). In 2003, a representative number (182 of 531 flocks) was again investigated. Seropositive flocks were treated with doramectin (0.3 mg/kg body weight). In 2001, 34 flocks (5.8%) were seropositive: 21 infested with *P. ovis*, one with *P. cuniculi*, four with *Chorioptes* spp. and eight had seropositivity of unknown origin. In 2002, the number of seropositive flocks decreased to 4.4%: 15 were infested with *P. ovis*, two with *Chorioptes* spp. and eight had seropositivity of unknown origin. Of the 182 flocks surveyed in 2003, just four (2.2%) were seropositive, all as a result of infestation by *Chorioptes* spp.

Sarcoptic mange

An ELISA for the serodiagnosis of sarcoptic mange (caused by *S. scabiei* var. *ovis*) in sheep

has been investigated; the assay has been shown to have a sensitivity greater than that recorded by skin scraping, with a positive correlation with lesion area (Rodriguez-Cadenas *et al.*, 2007). Infestations can be detected 2–5 weeks after challenge with half the animals seronegative after 3 months (Rodriguez-Cadenas *et al.*, 2007). An amplified ELISA has been developed to detect antibodies to *S. scabiei* in the serum of infested goats, using whole body extracts of *S. scabiei* isolated from the red fox (*Vulpes vulpes*); sensitivity and specificity were 93% and 99%, respectively (Rambozzi *et al.*, 2001).

Lice (*Bovicola ovis*)

A 'pen-side' test, based upon an ELISA method, has been developed in Australia to detect lice (*B. ovis*) based on the detection of louse-specific proteins deposited in wool (Sanderson, 2001). The greasy debris that accumulates on the combs and cutters of the handpiece during shearing is tested by an ELISA. Flocks can be tested at shearing to identify lousy flocks and confirm flocks free from lice. The test is extremely sensitive, but cannot differentiate between live or dead lice, and is not recommended for use after long-wool treatments.

Nasal bot flies (*Oestrus ovis*)

Bautista-Garfias *et al.* (1988) showed that *O. ovis* elicits an immune response in infested sheep. A serological diagnostic technique would therefore be useful in separating cases of oestrosis from more serious diseases, such as scrapie or listeriosis. A number of serodiagnostic techniques have therefore been investigated, including double diffusion (DD) and indirect haemagglutination (IHA) (Bautista-Garfias *et al.*, 1982; Jagannath *et al.*, 1989).

The reliability of an ELISA for serodiagnosing oestrosis has been studied by Deconinck *et al.* (1995), Duranton *et al.* (1995) and Goddard *et al.* (1999). Goddard *et al.* (1999) studied the effectiveness of a direct ELISA using a soluble protein fraction of a crude somatic antigen derived from first-instar (L_1) larvae. The initial results suggested that the serum antibody titres detected were a reflection of the previous completed life cycle rather than of live L_1 larvae found in the nasal turbinates at post-mortem.

Angulo *et al.* (2007) investigated the role of antigens in the salivary glands of *O. ovis*, and validated an ELISA to detect *O. ovis* using second-instar (L_2) somatic antigen (SAL_2), L_2 salivary gland antigen ($SGAL_2$) and third-instar (L_3) salivary gland antigen ($SGAL_3$). Sensitivities and specificities were obtained of 96.1% (±46.9%) for SAL_2, 99.0% (±25%) for $SGAL_2$ and 96.1% (±48.4%) for $SGAL_3$ (Angulo *et al.*, 2007).

Goat warbles (*Przhevalskiana* spp.)

The diagnosis of goat warbles (*Przhevalskiana* spp.) is traditionally through palpation of the skin to detect the presence of second (L_2) or third-instar (L_3) larvae in the back and the presence of larvae under the skin of goat carcasses. An ELISA was investigated by Navidpour *et al.* (2007), with sensitivity and specificity calculated as 86.6% and 98.9%, respectively, in the first 3 months of infestation – while infestations were in the first-instar (L_1) stage.

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8

Prevention

Domestic sheep and goats can be attacked by a number of ectoparasites, all capable of causing considerable distress and the possible death of the host. In the UK, all sheep and goat farmers are made aware of the *Codes of Recommendations for the Welfare of Livestock*, specific for sheep (Defra, 2003) and for goats (Defra, 1989), which emphasize the prevention and treatment of ectoparasites. As effective chemical treatments are available, sheep or goat owners could face prosecution for 'causing unnecessary suffering' if they neglect to prevent or treat for ectoparasites on their animals.

Control can be expensive, labour intensive and time-consuming. There are also legal requirements regarding health and safety and the environment. The latter itself can be prohibitively expensive. Then there is the question of acaricide/ectoparasiticide resistance.

Effective control depends on whether the ectoparasite is permanent (i.e. spending its entire life cycle on the host) or semi-permanent (i.e. those with at least one free-living life stage) (Table 1.5). This chapter is concerned mainly with the prevention of permanent ectoparasites, although there is a short section on husbandry methods for the prevention of semi-permanent ectoparasites at the end. Control methods for both types of ectoparasite are covered in detail in Chapters 9 and 10.

Flock Health and Welfare Plans

In the UK, owners of sheep and goats are advised to prepare a Flock Health and Welfare Plan (FH&WP), a written strategy for the management of animal health, for their flocks/herds. Formulation of the FH&WP must involve a veterinary surgeon from the start and must demonstrate the flock owners' awareness of their responsibilities in terms of livestock health management. However, evidence suggests that a large number of sheep flock owners still do not have a written FH&WP. A postal survey carried out by the Welsh Assembly Government (WAG) in 2006/7 highlighted that only 37% of producers questioned had a written FH&WP (Hybu Cig Cymru, 2007).

An effective FH&WP should include:

- The *identification* of all significant potential parasites and diseases that may affect the flock/herd.
- An outline of *prevention* measures to avoid the introduction of such parasites and diseases.
- An outline of what *treatments* would be used should these occur.
- The identification of how to *improve* overall flock health and reduce reliance on veterinary treatments.

The FH&WP must be continually assessed and updated. Keeping records is essential, e.g. annual records of the date and position of the first observed blowfly strike and tag number of the struck sheep can be extremely useful. Trend analysis can indicate changes in patterns of infestation and aid in future control strategies. The sheep industry and veterinary profession must provide the flock owner with regularly updated and easy to understand information on ectoparasite prevention and control. Information must also be available on the veterinary medicines defined in the FH&WP, particularly in relation to confirmed resistance in the local area.

Prevention

Permanent ectoparasites (mange mites – *Demodex*, *Chorioptes*, *Psoroptes*, *Psorobia* and *Sarcoptes*), lice (*Bovicola* and *Linognathus*) and keds (*Melophagus ovinus*) that spend their entire life cycle on the host, enter flocks or herds primarily through the introduction of or contact with infested animals. Thus, the relative risk of introducing a permanent ectoparasite to a flock or herd can (and should) be assessed. If a flock or herd is not involved in common (communal) grazing, the risk of introducing permanent ectoparasites can be reduced without the need for chemical intervention, through good biosecurity and the adoption of an effective closed flock policy.

Incoming stock

Permanent ectoparasites and other diseases can enter a flock or herd via newly purchased stock, overwintering stock (agisted or on tack), borrowed rams/billy goats returning home and stock returning from markets. All incoming stock should be observed for the clinical signs of ectoparasites before purchase/return and suspicious-looking animals closely examined. Sheep should be examined for scab mites (*Psoroptes ovis*) (Chapter 2) and/or lice (Chapter 4) according to the methods described in Chapter 7.

Newly purchased rams are a particular risk. In the UK, it is customary to purchase rams from ram sales between September and October, releasing them directly into the ewe flock to start working immediately on return to the holding – with no consideration for examination or quarantining! In Australia, it is considered essential to gather as much information as possible from the vendor on the recent louse and treatment history of purchased rams before purchase (Evans, 2007), as it is recognized that almost all new louse infestations occur through lousy sheep entering a flock or leaving and returning with lice. Stray sheep pose a very high risk as they may not show obvious clinical signs, but enter or leave the flock undetected. Without close surveillance, these sheep may remain undetected for a significant period (Evans, 2007).

If possible, livestock markets should be avoided and stock purchased directly from the vendor. Many animals can carry significant numbers of ectoparasites without presenting with obvious clinical signs. If the status of the source is doubtful, purchased stock should be quarantined, observed for clinical signs and treated if necessary.

Disinfection of transport lorries and trailers

Permanent ectoparasites can survive off the host for significant periods of time: at least 17 days in the cases of scab mites (*P. ovis*) (O'Brien *et al.*, 1994a) and chewing lice (*B. ovis*) (Morcombe *et al.*, 1994). It is important that all vehicles and trailers used to transport sheep/goats are thoroughly cleaned and disinfected after use. This is already a legal requirement in the UK for the prevention of viral infections such as foot-and-mouth disease, but pressure washing (particularly steam cleaning) and disinfection with a sodium hypochlorite or a peroxygen-based general disinfectant will also kill scab mites and lice.

Quarantine

In Britain, 38% of sheep scab (*P. ovis*) has been shown to be introduced to flocks through sheep movements, either via market purchases (22%), or direct sheep movements (16%) where sheep were over wintered away from the holding and came in contact with infested sheep (Bates, 2000a) (Table 8.1).

Evidence therefore suggests that the quarantining of all incoming sheep/goats will prevent mange and lice from entering the main flock. It is easier and less expensive to treat a small number of incoming animals than the whole flock/herd. A postal survey by WAG in 2006/7 highlighted that 68.5% of respondents quarantined bought-in or returning stock and 52.2% treated for ectoparasites while the animals were in quarantine (Hybu Cig Cymru, 2007). However, the WAG data also indicated that veterinary practices considered that less than 10% of their clients quarantined bought-in or returning stock (Hybu Cig Cymru, 2007). In Australia, quarantine is taken more seriously, with 91% of flock managers in South Australia claiming to take precautions to prevent the introduction of lice and a similar percentage routinely checking their flocks for lice (James and Riley, 2004).

Quarantine facilities can be a barn or other building, a yard or a dedicated paddock/field. It is essential that the facility is secure and that quarantined animals can have absolutely no contact with other animals. The WAG postal survey highlighted that 77.2% of respondents isolated animals in fields, 17.7% isolated them in sheds and 5.1% used both types of quarantine facility (Hybu Cig Cymru, 2007). The most popular treatment during quarantine was doramectin (37.2%). All incoming stock should be quarantined for a minimum of 4 weeks (if possible). During this quarantine period, the isolated animals should be observed for clinical signs of infestation (rubbing, scratching, deranged wool/fibre, areas of wool/hair loss, etc.).

Table 8.1. Origins of sheep scab infestations 1983–1988 (Source: Bates, 2000a).

Lateral spread – neighbours, strays, etc.	34.0%
Sheep movements via markets	22.0%
Obscure	18.5%
Direct sheep movements	16.0%
Under investigation (May 1988)	7.5%
Persistent infestations on common grazings	1.0%
Recrudescence	1.0%

If an ectoparasite is suspected, then the animal should be examined by a veterinary surgeon, the cause of the irritation investigated, an ectoparasite identified and the correct course of treatment prescribed. It must be borne in mind that sheep/goats may carry more than one ectoparasite (e.g. scab mites – *Psoroptes*, and lice – *Sarcoptes*) simultaneously. Administration of the incorrect treatment can be costly, both financially and as regards the possible development of drug resistance in both ectoparasites and endoparasites (gut worms). Isolated sheep/goats should only be released into the main flock/herd once the 4 weeks of quarantine is up or, if animals were confirmed to be actively infested, after any treatments are completed and the infestation shown to be cured.

If the treatment used offers residual protection against reinfestation (e.g. by scab mites for at least 21 days), the treated sheep can remain in the quarantine facility for the full 4 weeks during treatment. If the treatment does not offer this protection, the sheep must be moved to a clean paddock or housing directly after treatment to prevent reinfestation from mites (or lice) in the environment. In the UK, SCOPS (Strategic Control of Parasites of Sheep) promotes the isolation of all incoming sheep in a yard for 24–48 h and treatment for resistant gut worms and sheep scab by the administration of a moxidectin-based injection plus a levamisole-based wormer. Animals should then be turned out on to a pasture that has carried sheep this season and kept isolated for 3 weeks. This strategy should prevent the introduction of drug-resistant gut worms, as treating on arrival with the appropriate wormer kills most resistant worms – but not all, so putting them out to graze on 'dirty' pasture ensures the uptake of susceptible worms – thus diluting out the resistant ones. However, 3 weeks may not be sufficient for sheep to present with clinical signs of

ectoparasites, and a minimum of 4 weeks is therefore recommended.

Quarantining may not always be possible, particularly from the aspect of the availability of suitable facilities. It can also be expensive – as isolated stock need to be fed and watered. The length of the quarantine period is also significant, particularly in regard to scab in the asymptomatic subclinical phase – which lasts from 14 to 40 days under laboratory conditions and over 240 days in the field (Bates, 1999c, 2000a). Psoroptic ear mites should also be considered. Clinically normal sheep can carry *Psoroptes* in their ears and these mites may be responsible for a subsequent outbreak of scab within the flock (Bates, 2000b).

Incoming stock should be quarantined and examined for lice as described in Chapter 4. However, in early infestations, only a few animals will be infested and visual inspection is not always reliable. Animals with light infestations released into the main flock can produce significant flock/herd problems in the following years. It is essential, therefore, to prevent lice from entering the main flock. The use of a moxidectin-based injection under the SCOPS quarantine guidelines will prevent the introduction of sucking lice species (e.g. *Linognathus*); however, a topical application of effective ectoparasiticide will be required to control chewing lice (*Bovicola* spp.).

Quarantine buildings in which infested sheep/goats had been isolated should be thoroughly cleaned and disinfected once animals are released. Disinfect with a strong (sodium hypochlorite or peroxygen-based) disinfectant. All litter must be burnt or deposited out of sheep/goat contact and all tags of wool/fibre must be collected and burnt. The latter also applies to open quarantine paddocks. Sheep/goats should not be introduced into quarantine housing or paddocks for at least 3 weeks after disinfestation.

Persistent infestations on common/communal grazings

In the UK, common/communal grazings, shared by several flocks, are well known for persistent infestations of sheep scab (*P. ovis*) and chewing lice (*B. ovis*), usually the result of a small number of recalcitrant flock owners or of contact with feral sheep. Scab is generally slow to progress on the open-fleeced sheep breeds traditionally grazing common land, and the continual persistence of scab results in a significant number of sheep with an acquired resistance to previous scab infestations (Bates *et al.*, 2001b). Together, these factors result in long periods of subclinical scab. Although the confirmation of scab on common/communal grazings appears to be relatively low (Table 8.1), sheep moved off these grazings that are carrying subclinical infestations may be the cause of more severe scab in more susceptible lowland flocks. On common or unfenced grazing cooperation must be sought with neighbouring properties to attain equal standards of health. Wherever possible, all flocks on the grazing should be treated simultaneously.

Disinfection of clothing and equipment

As already mentioned, scab mites (*P. ovis*) (O'Brien *et al.*, 1994) and lice (*B. ovis*) (Morcombe *et al.*, 1994) can survive off the host for at least 17 days, and can be transmitted to other sheep/goats via infected material deposited in the environment.

It is, therefore, essential that anybody having contact with infested animals (shearers, contractors, veterinary surgeons, etc.) disinfects protective clothing, shearing combs and cutters, etc., before leaving the property, using strong sodium hypochlorite or peroxygen-based general disinfectant, sheep dip or, where suitable, boiling water. Scab mites (*P. ovis*) can survive on clothing and the human body (particularly under finger nails). Anybody having contact with an infested flock must wash exposed areas of skin with water (as hot as bearable) before leaving the premises. It is unwise to visit another sheep flock after contact with infested sheep without a hot shower and a complete change of clothing. In Australia, adults and nymphs of the chewing louse (*B. ovis*) have been shown to survive on

shearers' moccasins for up to 10 days; consequently, it is advised to microwave moccasins for 5 min to kill the potentially infestive lice (Crawford *et al.*, 2001) before leaving the property.

Effective well-maintained fences and walls

Data have shown (Table 8.1) that 34% of sheep scab cases in Britain originated from contact with infected neighbouring flocks and/or stray sheep (Bates, 2000a). Effective fencing/walling is essential to: (i) prevent straying on/off the holding; (ii) prevent contact with neighbouring flocks; and (iii) maintain closed flock integrity (and, where appropriate, organic status).

Fencing/walling must be well maintained, with the frequency of inspection and maintenance described in the FH&WP. This should also apply to fencing not directly owned by the flock owner, but still an integral part of the perimeter fence. Ideally, double fencing – two parallel lines a minimum of 1 m apart – is required for the perimeter fencing where there is a risk of contact with neighbouring flocks. The gaps between the fence lines are also extremely beneficial for native plants and wildlife and increase the holding's biodiversity. In most situations, permanent double fencing is not possible, but mobile electric fencing/netting could be considered – to be erected while sheep are at risk and dismantled when no longer required.

Introduction of a permanent ectoparasite into a flock/herd

If one sheep with subclinical scab is introduced into a scab-free flock it will not pass mites on to other sheep or the environment while the infestation is still subclinical. The lesion has to enter the rapid-growth phase, weeks or even months after the initial challenge, by which time the mite population is large enough to pass to naive sheep and the irritative effects of the lesion cause sheep to behave in a manner effective in depositing mites in the environment. Thus, scab is generally well embedded in a flock at the point of veterinary involvement (Bates, 2009a). Indeed, the results of a study investigating the epidemiology of scab within ten naturally infested sheep flocks in England and Wales showed that between 8% and 60% of sheep were infested at the point of veterinary intervention, with lesion areas ranging from 1.0 cm^2 to extensive body cover (Bates, 2009a).

Population densities of the chewing louse (*B. ovis*) can vary with time. A few lousy sheep within a flock or mob will not cause widespread, noticeable lousiness, even after a few months. With shearing and incomplete chemical control, a new infestation may even take years to be noticed. Beyond a certain point of infestation, uncontrolled louse populations can multiply rapidly.

Husbandry methods

Permanent ectoparasites have to enter a flock via contact with infested animals. Semi-permanent ectoparasites are part of the normal fauna of a farm or grazing and are not generally introduced through the introduction of or contact with infested animals. Blowflies and nasal bot flies (*Oestrus ovis*), for example, are able to fly several kilometres in search of a host. Semi-permanent ectoparasites are also generally less host specific.

The risk of semi-permanent ectoparasites such as blowfly strike can be reduced by good husbandry. These husbandry methods are described in more detail in Chapter 5, but are outlined below.

Regular flock examination

Flock observations should be carried out at least once a day during the fly seasons, but are time consuming, as care should be taken to observe the flock thoroughly for signs of infestation. Even animals treated with a preventive ectoparasiticide need to be inspected at least once a day as treatments have to breakdown eventually.

Shearing

Shearing will reduce the susceptibility of ewes to body strike while the fleece is relatively short. Shearing will also aid in the control of the permanent ectoparasite *B. ovis*, the sheep chewing louse. Populations of *B. ovis* decrease naturally with the onset of summer, and shearing can also reduce residual lice populations by 36–66%. The optimal time for chemical treatment is thus immediately after shearing (Heath *et al.*, 1995b).

Crutching and dagging

The risk of breech strike can be reduced through crutching or dagging from early in the fly season and then repeating every 4–6 weeks to remain effective.

Tail docking

Tail docking (to not shorter than 4 inches), will also reduce the incidence of breech strike.

Prevention of skin infections

Good husbandry in preventing other skin infections will greatly benefit strike control.

Control of scouring

Effective control of intestinal parasites would reduce scouring. Control of scouring caused by changes in diet and digestive disturbances due to lush grass is also essential.

Culling susceptible sheep

Individual sheep can be struck twice, three or more times if they are not treated. Some evidence points to the possibility that some attraction factors are hereditary and that breeding ewes and rams which are continually struck should be culled.

Housing

Unlike other species of blowfly, *Lucilia sericata* will not enter areas of low light intensity. Consequently these blowflies are rarely encountered in houses or barns. Housing sheep during fly waves could reduce the prevalence of breech or body strike.

Removal of carcasses

All carcasses, large and small, should be removed and incinerated as these will augment the natural population of blowflies in the immediate area. The carcasses must also be legally disposed of in order to minimize ovarian development in adult flies and the build-up of alternative generations.

Foot rot control

Cases of foot rot should be attended to immediately. Although foot strike is medicinally beneficial (because the maggots eat away the infected tissue), they will also subsequently augment the natural population of blowflies in the immediate area.

Trapping

Trapping may reduce (but will never eradicate) the numbers of blowflies attacking sheep and can be used to monitor fly activity, thus aiding the timing of preventive treatments (see Chapter 10).

9

Chemical Control

Ectoparasiticides

A variety of chemicals have been used for the control of sheep and goat ectoparasites. These chemicals are collectively known as ectoparasiticides and, with respect to the control of sheep and goat ectoparasites, can be classed as acaricides (killing the acari – mites and ticks) or insecticides (killing insects – lice, flies, fleas or keds). In this book, acaricides and insecticides are referred to collectively as ectoparasiticides.

Early developments

In 1843, the first arsenic/sulfur dispensable powder dip – an inorganic treatment – was manufactured in the UK by William Cooper and was widely used throughout the world for over a century. In the following two decades, other inorganic treatments – nicotine/sulfur, nicotine/arsenic and lime/sulfur dips – were introduced. By 1904, government-approved formulations in the UK for the control of sheep scab mites (*Psoroptes ovis*) contained a variety of compounds – arsenic, sulfur, crude phenols, tar oils, tar acids, and tobacco or derris root.

Arsenical dips were intended to be true solutions which, apart from their direct acaricidal activity, rendered the microclimate unsuitable for ectoparasites by hardening and roughing the skin. Attention had to be paid to open wounds as solutions were fatal if absorbed directly into the bloodstream. Arsenical dips were also slow to act, with mites surviving for a few days after treatment. Crude phenols, tar oils and tar acids were sparingly soluble and usually applied as an emulsion.

In practice, most farmers used proprietary dips on account of their general convenience. Sodium arsenite was the standard ectoparasiticide in 1945, but arsenic/sulfur, lime/sulfur, rotenone or cresolic acid were also widely employed. In each case, it was important to follow the instructions from the manufacturer closely. Some shepherds were inclined to use stronger solutions than recommended, often in the unfounded belief that it was possible to kill eggs as well as mature parasites. However, no dipping agent was effective against eggs. It was impossible, therefore, to use a dip that was strong enough to kill eggs without grave risk to poisoning the sheep. Two dippings were essential, with intervals long enough to kill all hatched larvae but not too long to allow adult females to develop: ideally the interval was 8–14 days (Spence, 1951). Arsenic-based dips were still widely used in Australia until they were deregulated in 1987 (Levot, 2000).

Plant derivatives

Ectoparasiticidal ingredients extracted from plants can be active through contact and are relatively non-toxic to mammals. Examples of active plant extracts are derris, pyrethrins, rotenone and nicotine.

Pyrethrins are extracted from the flower heads of chrysanthemums. The product pyrethrum is a mixture of four pyrethrins, pyrethrins I and II and cinerin I and II (Ware, 1978), and can have some repellency action and rapid knock-down (Kd) characteristics (Harewood and James, 1980). When it is used alone, 'downed' insects may recover. Consequently, synergists are added to prevent insect survivors from degrading pyrethrin and recovering. Despite their long use and study, the mechanism of action of pyrethrins is still relatively unknown. The quick Kd of flying insects is the result of rapid paralysis, which could be through an effect on either muscles or nerves (Ware, 1978).

The rotenoids are produced by two genera of the legume (bean) family: *Derris*, grown in Malaysia and the East Indies, and *Lonchocarpus*, grown in South America (Ware, 1978). Rotenone was popular for over 50 years but fell out of favour owing to questionable physiological effects observed in laboratory animals fed the compound over an extended period (Ware, 1978). It is highly toxic to most insects, and its mode of action is interference in energy production through its action on the electron transport chain and, thereby, the phosphorylation of adenosine triphosphate (ATP) (Ware, 1978).

Organochlorine (OC) formulations

Between World Wars (WW) I and II, the toxicity of arsenical and coal-tar products and the need to produce a grade of sulfur of optimal biological efficacy prompted extensive research into more effective dip formulations, primarily the chlorinated hydrocarbon (organochlorine – OC) ectoparasiticides. Widely used OCs included aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, lindane and toxaphene.

DDT (1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)ethane; formerly known as dichlorodiphenyl-trichloroethane, hence DDT), is a diphenyl aliphatic compound that was introduced in 1939 (Ware, 1978), and was effective against lice and blowfly larvae but ineffective against scab mites (*P. ovis*) (Downing, 1947).

Lindane (chemical names: γ-BHC – γ-benzenehexachloride; γ-HCH – γ-hexachlorocyclohexane or 1,2,3,4,5, 6-hexachlorocylohexane) was first discovered in 1825, but was not known to have insecticidal properties until 1940. Towards the end of WWII, trials began with lindane for the control of sheep scab (caused by *P. ovis*), and in 1948 the first lindane-based dips were officially approved in the UK for sheep scab control (Downing, 1947). A single dipping in wash that contained 0.016% lindane was shown to be 100% effective in curing scab (Kirkwood, 1986); it eradicated *P. ovis* and left sufficient chemical residual in the fleece and skin to kill *P. ovis* eggs on hatching for a considerable number of weeks after dipping (Spence, 1951; Page, 1969). Sheep scab was eradicated from Britain (not including Northern Ireland) in 1953, after 7 years of compulsory dipping in formulations containing lindane. The disease returned to Britain in 1973, and lindane was once again at the forefront of scab control. In 1982, a number of 'off-the-shelf' lindane formulations were assessed under the contemporary Sheep Scab Dip Approval Protocol. Two of the best-selling formulations failed to cure sheep scab completely (Kirkwood and Bates, unpublished data). By 1984 though, all 90+ lindane formulations on the UK market were 'licensed by right' and not tested for efficacy against *P. ovis*.

Another group of OC compounds, the cyclodienes, were developed after WWII and are, therefore, more recent than DDT (1939) or HCH (1940); these included chlordane (1945), aldrin and dieldrin (1948), heptachlor (1949) and endrin (1951) (Ware, 1978). The polychloroterpene toxaphene was introduced in 1951 (Ware, 1978). Cyclodienes were found to be persistent ectoparasiticides and were stable in the soil and relatively stable to the ultraviolet

action of sunlight (Ware, 1978). It was a popular myth among sheep farmers in the UK that dieldrin was effective against sheep scab and that it played an important contribution to the eradication of scab in the 1950s. In fact, dieldrin neither cured nor protected against sheep scab, although it did have excellent efficacy against lice and blowfly larvae. Scab was eradicated from the UK in 1953, but dips containing dieldrin only entered field efficacy trials in 1953 and the first dieldrin dip was marketed (for blowfly control) in 1954.

OCs were mostly active through contact with the target ectoparasite, but the exact mode of action was not clearly understood (Harewood and James, 1980). They were thought to act upon the neurons by destroying the delicate balance of sodium and potassium within the cell, thus preventing the normal transmission of nerve impulses, and eventually causing neurons to fire impulses spontaneously, leading to muscle twitching, convulsions and death. The prolonged contact toxicity of OCs led to their withdrawal. They destroyed susceptible ectoparasites so successfully that this led to extreme selection pressure and, in the end, resistance. OCs were also shown to distribute widely in the environment and to accumulate at increasing rates higher up the food chain (Harewood and James, 1980). The cyclodienes were withdrawn from the UK market in the late 1960s, primarily on environmental grounds, and banned in Australia in 1957 (Levot, 2000). Lindane-based dips continued to be used in the UK until December 1984, when they were voluntarily withdrawn following pressure from Europe over possible residues in exported lamb (Henderson, 1991).

Strains of *P. ovis* resistant to lindane were reported in Argentina in 1962 (Ault *et al.*, 1962), and severely hampered scab control (Nuñez, 1977). In contrast, during the 18 years of compulsory use against sheep scab in the UK, no cases of lindane resistance in *P. ovis* were ever recorded. However, the intensive use of lindane-based plunge-dip formulations for scab control and the popularity of lindane, DDT, aldrin and dieldrin between 1953 and 1972 (administered through plunge dips, spray races or shower dips) selected for OC resistance in chewing lice (*Bovicola ovis*) in north-west England (Barr and Hamilton, 1965). Resistance to the OC ectoparasiticide dieldrin was reported in *Lucilia cuprina* in Australia 1958, New Zealand in 1961 and the Republic of South Africa in 1964, and in *Lucilia sericata* in the Republic of Ireland in 1968 (Shaw *et al.*, 1968).

The popularity of lindane waned worldwide and scab control changed in favour of the new organophosphate (OP) formulations, such as diazinon (Page, 1969).

Organophosphate (OP) formulations

The OPs were the next generation of ectoparasiticides, characterized by less build-up in the food chain than the OCs, and eventually more OPs were synthesized as ectoparasiticides than any other group of compounds (Harewood and James, 1980). The OPs are all derived from phosphoric acid and have two distinctive features. First, they are generally much more toxic to vertebrates than the OCs and, secondly, they are chemically unstable and relatively less persistent than the OCs (Ware, 1978). The OPs can be divided into three classes: aliphatic, phenyl and heterocyclic derivatives (Ware, 1978).

- The aliphatic derivatives include malathion, one of the safest of the OPs, and trichlorfon.
- The phenyl derivatives include ronnel and crufomate, systemic ectoparasiticides effective against warble larvae (*Hypoderma* spp.) in cattle.
- The heterocyclic derivatives include diazinon and chlorpyrifos; these have longer lasting residues than many of the aliphatic or phenyl derivatives.

Diazinon was approved for sheep scab control in the UK in 1981 (Kirkwood and Quick, 1981), although it had been licensed for blowfly and louse control since the early 1970s. Propetamphos was approved for scab,

louse and blowfly control in the UK in 1982 (Kirkwood and Quick, 1982). Another OP, sebacil (phoxim), is currently licensed for scab control in Europe, but not the UK or the Republic of Ireland.

The insecticidal action of the OPs was first observed in Germany during WWII, in the study of compounds closely related to the nerve gases sarin, soman and tabun. Initially, the discovery was made during the search of substitutes for nicotine, which was in critically short supply. OPs exert their toxic action by inhibiting cholinesterase (ChE). Throughout the insect or mammalian nervous systems there are electrical switching centres (synapses) where the electrical signal is carried across a gap to a muscle or another neuron by a chemical, acetylcholine (Ach). After the electrical impulse has been conducted across the gap by Ach, ChE moves in quickly and removes the Ach, thus preventing the 'circuit jamming'. These chemical reactions happen extremely rapidly and go on constantly under normal conditions. OPs attach to ChE, preventing the removal of Ach, and thus 'jamming the circuit' through the accumulation of Ach. This accumulation interferes with the neuromuscular junction, producing rapid twitching of voluntary muscles and, finally, paralysis. This process is of particular importance in the proper functioning of the respiratory system.

OP dip formulations began to be incriminated in post-dipping illness in stock owners and contractors (Anon., 1989) and, consequently, safer ectoparasiticides were investigated for their efficacy against scab, lice and blowfly strike. OP dips were temporarily withdrawn from the British market in 2000 in order for manufacturers to improve their delivery systems. It was recognized that serious sheep health and welfare problems would occur if OP dips were withdrawn permanently. It is now a legal requirement in Britain to use closed transfer systems when handling dip concentrate; these were developed by the manufacturers and introduced in 2001. In May 2007, the use of shower or plunge-dip formulations containing diazinon for the control of lice were discontinued in Australia for health and safety reasons. However, diazinon products could still be used as pour-on (backline) treatments.

Strains of the sheep scab mite (*P. ovis*) resistant to the OP diazinon were first reported in Argentina in 1970 (Rosa and Lukovich, 1970). In the winter of 1995, a strain of scab mite (*P. ovis*) resistant to the OP propetamphos was isolated from a flock in Caithness, Scotland (Clarke *et al.*, 1996). However, controlled dipping trials demonstrated that this population was still susceptible to diazinon (Bates, 1998). With the subsequent increase in the use of OPs, a population of *B. ovis* was identified in Australia with a resistance factor (RF) at LC_{50} of 9× to diazinon (Levot, 1994). OP resistance in *L. cuprina* appeared in Australia in 1965 and in South Africa in 1968, and is now widespread in both countries.

OP dips are totally prohibited by organic certifying bodies in the UK, and organic certification will be withdrawn if they are used (Soil Association, 2009).

Synthetic pyrethroid (SP) formulations

The early pyrethrins were rapidly broken down by sunlight and the first photostable pyrethrin analogues (synthetic pyrethroids, SPs) were reported in the 1970s. All SPs are carboxylic acid esters with high toxicity to arthropods and relatively low mammalian toxicity. The first photostable SP formulations, permethrin and fenvalerate, are still widely used for the control of crop pests and arthropods of medical and veterinary importance. Examples of SPs include alphacypermethrin, cypermethrin, deltamethrin, fenvalerate, flumethrin and permethrin.

SPs affect the neuronal membrane, modifying the sodium channels, and probably impeding protein conformational changes at the lipid–protein interface, resulting in the sodium channels closing more slowly and causing a delayed inward sodium current, resulting in paralysis and death. This action is similar to that of OCs. Both DDT and SPs have two types of insecticidal effect: (i) initial rapid Kd, rendering the insect motionless; and (ii) a subsequent

lethal effect. Both of these effects are more effective at lower temperatures.

Plunge-dip formulations containing the SP flumethrin, were approved for sheep scab control in 1987 (Kirkwood and Bates, 1987a). Later, dip and pour-on formulations containing high-cis cypermethrin (also known as HCC) were licensed for the British market for ectoparasite control. The biggest advantage of SPs is that they can also be formulated as pour-ons or spot-ons, thus revolutionizing ectoparasite control on sheep and goats. Pour-on formulations of SPs (alpha-cypermethrin, cypermethrin, deltamethrin) are available worldwide for the control of headflies, ticks, lice, keds and blowfly strike.

The development of resistance to DDT by pests around the world was thought by many to foreshadow a similar fate for the SPs (Miller, 1988). In Britain, sheep scab mites (*P. ovis*) developed resistance to the SP flumethrin in 1994 (Synge *et al.*, 1995; Bates, 1998). The failure of SP-based pour-ons and plunge dips to control sheep chewing lice (*B. ovis*) was first reported in Australia and New Zealand in the late 1980s (Levot, 2000), and in Britain in 2004 (Bates, 2004).

SP pour-ons/spot-ons (alpha-cypermethrin, cypermethrin and deltamethrin) are all approved by the UK Soil Association for the organic control of lice (*B. ovis*) and the prevention of blowfly strike (Soil Association, 2009).

Amidines (formamidines)

The amidines inhibit monoamine oxidase, resulting in the accumulation of biogenic amines, whose actions are not fully understood. They may act in certain instances as chemical transmitters (similar to acetylcholine) at synapses (Ware, 1978). The commonest member of this group, amitraz (*N*, *N*-di (2,4 dimethylphenyliminomethyl)-methylamine), has been shown to be effective against *Psoroptes*, *Sarcoptes* and *Chorioptes*. Clinical trials carried out in Argentina, France, Inner Mongolia and Syria have demonstrated that a 12.5% formulation (at an initial concentration of 0.05%) was 100% effective in curing sheep scab mites (*P. ovis*), but only after two dippings 10 days apart (Muñoz-Cobénas *et al.*, 1978; Curtis, 1985). Although effective, amidines are very expensive and are only used as 'OP resistance breakers'. Additionally, the dipwash has to be stabilized in the dip bath using calcium hydroxide.

Macrocyclic lactone (ML) formulations

Macrocyclic lactones (MLs) are fermentation products of soil microorganisms (*Streptomyces* spp.) and have been chemically modified to produce the avermectins (ivermectin and doramectin) and the milbamycins (moxidectin), which have a greater potency and broader spectrum antiparasitic activity than their fermentation precursors (abamectin and nemadectin, respectively). MLs are true systemic ectoparasiticides but can also act through contact. They are effective against ectoparasites that require frequent feeding on the host's blood.

The first ML to be licensed for scab control was ivermectin (derived from *Streptomyces avermitilis*); two subcutaneous injections were given 7 days apart (Bates and Groves, 1991; Soll *et al.*, 1992; O'Brien *et al.*, 1993). Unfortunately, ivermectin offers little or no residual protection against reinfestation, therefore sheep must not be returned to infested pens/pastures for at least 17 days.

The next ML to be developed and licensed for scab (curative) control was doramectin; this was curative after a single intramuscular injection (Bates *et al.*, 1995b; McKenzie, 1997). Noticeable failures of doramectin have been recorded in France, where it was administered as a single subcutaneous injection at 200µg/kg body weight (Personne, personal communication). In the UK, doramectin is administered as an intramuscular injection at the higher rate of 300µg/kg body weight. Although the recommendations for doramectin only require one injection in Europe, two injections are required in Argentina. Studies in neighbouring Uruguay have demonstrated

that a single, intramuscular injection of doramectin at 200 or 300µg/kg body weight were 100% effective in controlling artificial infestations of sheep scab (Cardoza *et al.*, 2000).

Single or double subcutaneous injections of the milbamycin moxidectin (derived from *Streptomyces cyaneogriseus*) have been shown to both cure scab and provide residual protection against reinfestation for 28 days (O'Brien *et al.*, 1994b, 1996; Williams and Parker, 1996; Parker *et al.*, 1999). Moxidectin does not possess the disaccharide side chain (present in all the avermectins) and has unique side groups: a methoxine group and a dimethylbutenyl group. These subtle differences in molecular structure give rise to markedly different pharmacokinetics and potency properties of moxidectin compared with the avermectins.

MLs are generally formulated as oral drenches, subcutaneous or intramuscular injections, constant release capsules (CRCs) and formulations for shower dips and automatic or hand jetting. Injections of MLs have advantages over plunge dipping in that they are quicker and safer to use, cause less stress to the sheep (including pregnant ewes) and do not require any special handling facilities and fixed equipment (i.e. dip baths); there is also not the same environmental concerns over the disposal of spent products (Bates, 1993). They have the added advantage that they are effective broad-spectrum anthelmintics as well. Consequently, ML formulations are often referred to as endectocides: having efficacy against both internal endoparasites and external ectoparasites. Their main disadvantage is their relatively narrow range of efficacy against ectoparasites and the alternative compounds may be required for the control of lice, ticks and blowflies. In addition, they have relatively long meat withdrawal periods (Bates, 1993). The fact that sheep scab is a form of allergic dermatitis also means that although MLs can eradicate *P. ovis* from infested sheep, the sheep can still suffer irritation for some time after treatment (Bates and Groves, 1991).

Oral drenching with ivermectin can produce a 48% drop in scab mite (*P. ovis*) numbers within 24h of treatment, but there is little further decline and no relationship between the initial mite burden and the extent of control (Bates and Groves, 1991). The apparent inefficacy of oral ivermectin may have significant effects on the epidemiology of sheep scab by extending the subclinical phase or selecting for resistance to other endectocides administered by injection (e.g. doramectin, ivermectin or moxidectin).

MLs as injections are the only formulations currently approved by UK Organic Standards for the control of sheep scab (*P. ovis*), but only if described in the FH&WP (Flock Health and Welfare Plan) under derogation from the organic certifying body and with a plan to reduce future reliance (Soil Association, 2009).

In vitro bioassays have shown that ivermectin and abamectin are highly effective against *B. ovis*, and similar responses of pyrethroid-susceptible and pyrethroid-resistant strains indicated that there was no cross resistance to ivermectin (Rugg and Thompson, 1993).

Salicylanilides

Like the MLs, the salicylanilides (e.g. closantel) have both anthelmintic and insecticidal properties; they are effective against sucking lice (*Linognathus* spp.) (Butler, 1986), larvae of the nasal botfly (*Oestrus ovis*), and parasitic nematodes and trematodes. Closantel binds strongly and almost exclusively to serum albumin, with a half-life of 2–3 weeks. It affects mitochondrial energy production by inhibiting oxidative phosphorylation and thereby ATP synthesis (Maes *et al.*, 1988). Closantel is generally administered as an oral drench.

Insect growth regulators (IGRs)

Insect growth regulators (IGRs) interfere with various aspects of arthropod growth and development, principally embryonic, larval or nymphal development, and disrupt metamorphosis and reproduction

(Wall and Shearer, 2001). IGRs fall into four categories:

1. *Juvenile hormones and juvenile hormone analogues.* Juvenile hormones and juvenile hormone analogues (e.g. methoprene, fenoxcarb and pyriproxen) show a high degree of species specificity. They switch 'on' and 'off' throughout the insects' larval development. Removal can induce early pupation, resulting in dwarf adults. An excess of juvenile hormones in mature larvae may postpone or suppress metamorphosis altogether; the presence of juvenile hormones may also prevent egg hatch (Wall and Shearer, 2001).
2. *Chitin synthesis inhibitors.* Chitin is an important component of the arthropod exoskeleton; it does not occur in vertebrates and is thus a possible parasite-specific target of low mammalian toxicity. Chitin synthesis and degradation are controlled by moulting hormones (ecdysteroids). Ecdysteroids used in high concentrations cause disturbances in cuticle formation and may lead to lethal effects during the next moult. Chitin synthesis inhibitors (e.g. diflubenzuron, triflumuron and lufenuron) target the ectoparasite cuticle. The benzoyl phenylureas (BPUs) disrupt chitin synthesis by preventing the production of chitin microfibrils (Wall and Shearer, 2001). Target ectoparasites die at egg hatch or moult.
3. *Triazine derivatives.* Triazine derivatives (e.g. cyromazine) interfere at moulting and pupation, but without acting directly on chitin synthesis. Unlike BPUs, which act on a wide range of ectoparasites, the triazine derivative cyromazine is only active against larvae of the higher Diptera. Cyromazine causes epidermal cells of third instar (L_3) blowfly larvae to invade the cuticle and produce necrotic lesions, whereas diflubenzuron inhibits cuticle synthesis and thus results in the secretion of an imperfect cuticle.
4. *Pyrimidinamines.* The pyramidinamines (e.g. dicylanil) interfere with chitin metabolism in a way that is not yet fully understood. Dicylanil is effective against *L. cuprina*, *L. sericata* and *Wohlfarhtia magnifica.*

IGRs should only be applied to prevent blowfly strike. They are not effective in killing existing strike larvae. Some IGRs (e.g. triflumuron) have been shown to inhibit egg hatch.

In the UK, IGRs can be used prophylactically by organic producers as part of an FH&WP where there is a risk of blowfly strike and evidence of actual risk (i.e. veterinary declaration). Cyromazine is permitted without prior permission from a UK organic certifying body. However, dicyclanil requires prior permission (Soil Association, 2009).

Resistance to IGRs can occur (Cerf and Georghiou, 1974). Populations of *L. cuprina* resistant to the IGR diflubenzuron were reported in Australia in 1999.

Spinosyns

The spinosyns are currently represented by spinosad. In Australia, spinosad has recently been registered for the control of chewing lice (*B. ovis*) and blowfly strike (by *L. cuprina*). Spinosad offers a fast kill, with 98% of lice killed within 8 h. The product can be applied to any fleece length, has no meat or fleece withdrawal period and therefore no occupational health and safety issues for shearers or wool handlers. Spinosad administered by hand jetting cures existing fly strike and prevents further challenge for 4–6 weeks.

Synergists

Ectoparasiticide resistance is often due to the enhancement of metabolic enzyme systems within the ectoparasite – mixed-function oxidases, particularly microsomal oxidases, and non-specific esterases. These enzymes are present in many ectoparasites, and enable them to metabolize environmental xenobiotics.

Synergists (such as piperonyl butoxide, PBO) are non-toxic chemicals that inhibit the insects' enzyme systems, resulting in greater toxicity of an ectoparasiticide. They were originally developed for use with pyrethrin, but have been observed to synergize some, but not all, SPs, OPs and OCs.

It has been well established that the synergist's mode of action is the inhibition of mixed-function oxidases. In ectoparasiticides, this metabolism leads either to detoxification or activation. Thus, if the inhibited enzyme generally detoxifies the ectoparasiticide, the ectoparasiticide is left intact to exert its effectiveness, and appears synergized. Conversely, if the inhibited enzyme normally activates the ectoparasiticide, the enzyme is not activated, and appears to be inhibited or antagonized in its effectiveness (Ware, 1978). Synergists are commonly used to reduce costs.

Formulations

An active chemical (active ingredient) is manufactured in a relatively pure form (technical-grade material) and has to be formulated into a usable form for direct application, or diluted before application. The formulation is the final physical condition in which the ectoparasiticide is sold for use. Formulation is the processing of an ectoparasiticide compound by any method that will improve its properties of storage, handling, application, effectiveness or safety (Ware, 1978). Apart from the active ingredient, formulations may also contain wetting or spreading agents, stabilizers, solvents and bacteriostats.

An ectoparasiticide is only effective if formulated correctly. An active ingredient may be highly effective against an ectoparasite, but can be next to useless if it is not presented to the ectoparasite at optimal concentrations. Formulations can also vary with respect to their intended method of application. Thus, an active ingredient may be formulated for use as a plunge dip, shower dip, jetting fluid, pour-on, injection oral drench or CRC.

Methods of Application/Administration

In the 19th century, ectoparasite control consisted of dressing individual sheep with smears or salves based upon hellebore, mercury, lime, nicotine, tar, turpentine or arsenic. Some of these were also used to hand-wash sheep (e.g. lime-nicotine wash was recommended).

Modern ectoparasiticide formulations can be administered to sheep or goats by a number of different, more effective, methods. The oldest methods depend on saturating the fleece/hair with wash containing diluted ectoparasiticide. These saturation methods include plunge dipping, shower dipping, automatic jetting and hand jetting. More modern (non-saturation) methods for the administration of ectoparasiticides include pour-ons (backline treatments), spot-ons, injections, oral drenches or intra-ruminal constant dose capsules. The administration of ectoparasiticides by non-saturation methods appeal more to sheep/goat farmers in arid areas, where water is scarce and saturation methods may not be possible.

Saturation methods

Saturation methods for ectoparasite control in sheep and goats, plunge dipping, shower dipping, automatic jetting races (AJRs) and hand jetting (and in some cases spray-on techniques) all follow the same basic principles. The ectoparasiticide is purchased as a highly concentrated liquid (the 'concentrate'), often in large volumes, which is then diluted in water to achieve the required working dilution, which is always in considerably larger volumes. This working dilution (the 'dipwash') is then applied, via a dip, shower, AJR or hand jetter, to achieve complete saturation of the sheep or goat to skin level. Effective application always depends on the relative wool/fibre length on the sheep/goat at the time of treatment. Application to off-shears (i.e. within 30 days of shearing) or animals with short wool (under 6 weeks off-shears, fleece length 1.0–1.5 cm) will result in less dipwash retained in the wool/fibre, but a quick effective kill and the possibility of eradicating permanent ectoparasites such as chewing lice (*B. ovis*) or scab mites (*P. ovis*). Application to animals with long wool (over 6 weeks off-shears, fleece length >1.5 cm) may take longer to kill ectoparasites,

complete eradication may not be achieved (through the dipwash not penetrating to skin level), but significantly higher residues of ectoparasiticide will be deposited in the exposed fleece and thus there is an increased period of protection against (re)infestation.

Plunge dipping

The first recorded case of plunge dipping (the total immersion of the sheep in ectoparasiticide wash) in the UK was in 1800 when Lord Summerville dipped sheep in Norfolk, in a bath containing arsenic, soft soap and water. Plunging sheep in baths of ectoparasiticide continued to be the most effective method of sheep ectoparasite control throughout the world for well over 150 years.

There is no doubt that plunge dipping is labour intensive and time-consuming (with an annual labour profile for a UK lowland flock of 250 ewes of 25 h annually), and hazardous to human health, but it still remains the only economic and effective method of controlling sheep ectoparasites. It can also be used to control the ectoparasites of angora goats. However, in recent years there has been an apparent decline in the use of plunge dipping and an increase in the use of alternative methods for the control of sheep ectoparasites (French *et al.*, 1994a).

The biological efficacy of plunge dipping depends on the deposition of the correct dose of ectoparasiticide on to the skin and fleece/fibre of each animal. Factors such as dip formulation, dip-bath volume, immersion time, dipwash concentration, wash fouling, length of fleece and grease content can all affect ectoparasiticide deposition. Kirkwood (1985) stated that scab eradication in the UK was achieved in 1953 not because every sheep had been dipped, but because every infested sheep had been dipped. He further stated that one of the main reasons why sheep scab was not eradicated the second time that it occurred was not so much a failure to dip properly but a failure to catch and dip every sheep. However, when sheep scab re-entered Britain in 1973 there was still a lack of knowledge on how plunge dipping actually worked and consequently of the necessary steps required for an effective dipping. There was also an element of cutting corners to save time and money.

In order to monitor the efficacy of plunge dipping to control sheep scab mites (*P. ovis*) data were collected on the relative levels of the OPs diazinon or propetamphos in wool samples taken from randomly selected sheep at livestock markets in England, Scotland and Wales between the years 1984 and 1988. The results for 1985 revealed that only three out of four sheep were dipped properly and that nationally 26–37% of flocks were inadequately treated (Anon., 1986). In 1990, a survey of dip usage in Northern Ireland demonstrated that 65% and 68% of randomly selected dipwash samples contained less than the manufacturer's recommended maintenance concentrations for propetamphos and diazinon, respectively. The concentrations found in fleece were also lower than those found in sheep dipped with the recommended concentrations of propetamphos and diazinon under controlled conditions (Blanchflower *et al.*, 1990).

PLUNGE-DIPPING FORMULATIONS. Plunge-dipping formulations of ectoparasiticide can be formulated as solutions, wettable powders (WPs) or emulsifiable concentrates (ECs). The early plunge dips were solutions of the active ingredient (e.g. arsenic) dissolved in water. Later WPs consisted of inert carriers impregnated with active ingredient, together with a wetting agent that had to be agitated in order to keep the active ingredient in suspension (Harewood and James, 1980). WPs containing lindane were available up to 1984. ECs are bound to a carrier substance, usually oil based which, together with an emulsifier (similar to detergent), aids in the formation of microscopically small droplets of ectoparasiticide in an emulsion. When added to water, the emulsifier causes the ectoparasiticide complex to disperse uniformly throughout the water, and when agitated, the dip has a milky appearance. EC dips must be mixed thoroughly for at least 5 min or more.

DIP BATHS (DIP TANKS, DIP VATS). Dip baths can be permanent (static) or mobile. There are three general types: short swim through,

long swim through and circular. Short swim through baths are generally for small flocks, and hold one or two sheep at a time. These baths are very labour intensive, as sheep need to be moved around in the bath for total fleece penetration. Long swim through baths are less labour intensive, requiring less manipulation of the sheep. Long swim through baths require a gate at one end and sheep must not be able to turn around or overtake one another. Circular baths offer better control over the sheep, leading to more accurate immersion times. Short swim baths and circular baths, with a capacity to hold 900–2250 l of dipwash, are very common in the UK.

DIPWASH CONCENTRATIONS. Three critical dipwash concentrations are recognized (Kirkwood and Bates, 1987b):

1. *The initial concentration (IC):* the make-up concentration of the bath (according to the manufacturer's instructions) before the addition of sheep.
2. *The minimum lethal concentration (MLC):* the lowest concentration of ectoparasiticide in dipwash that is lethal to the ectoparasite. This is derived at by dose titration studies on ectoparasite infested sheep.
3. *The maintenance concentration (MC):* a concentration defined by the dip manufacturer as 'the lowest concentration likely to be maintained under field conditions when the label instructions are followed', i.e. by maintaining the MC the MLC will never be reached.

DIP APPROVAL. Before 1992, all dip formulations in the UK for the control of sheep scab mites (*P. ovis*) had to be government approved in addition to gaining a Marketing Authorisation (MA). In order for a product to gain scab approval the maintenance level of the formulation must be able to:

- Cure active infestations by killing all extant *P. ovis* immediately and resolve the lesion within 56 days.
- Protect against reinfestation on sheep with 1.0 cm of fleece. The required period of protection before 1982 was 58 days (Kirkwood, 1985), between 1982 and 1988 it was 28 days (Kirkwood, 1985) and after 1988 it was 21 days.

These tests were carried out both in the laboratory and in the field. All scab approvals were carried out at the VLA (Veterinary Laboratories Agency), Weybridge, and between 1945 and 1992 only four active ingredients – lindane (OC), diazinon (OP), propetamphos (OP) and flumethrin (SP) – gained scab approval. In 1992, sheep scab was deregulated as a notifiable disease in the UK and the need for additional scab approval was no longer necessary.

DEPOSITION OF ECTOPARASITICIDE. Plunge dipping was thought to work by the mechanical sieving or filtering of the dip emulsion as the sheep drained, retaining ectoparasiticide and returning dipwash, weak in ectoparasiticide, back to the dip bath (Liebisch *et al.*, 1978). Studies at the VLA have, however, suggested that this traditional view may not be accurate as the concentration of active ingredient in the run off does not differ significantly from the concentration found in the dip bath at the same time.

Ectoparasiticide is preferentially absorbed into the skin/wool grease while the animal is in the dip bath (Kirkwood and Bates, 1987b; Bates, unpublished data), and sheep will take out between 18 and 32 l (4 and 7 gal.) of dipwash (depending on the size and breed of sheep, and length of fleece), retaining 1 to 4.5 l (0.25 to 1.0 gal) in the fleece. One hundred sheep can therefore remove between 100 and 450 l of dipwash. As the fleece lipid is already loaded with active ingredient, excess active ingredient in the dipwash has nowhere to go; it is not firmly bound and can therefore be washed out with heavy rainfall, or become a dry powder that is brushed off into the environment over a period of weeks.

The dipwash not only loses volume but becomes progressively weaker in ectoparasiticide concentration as successive sheep pass through the wash. This phenomenon is known as 'stripping' ('depletion' or 'exhaustion'). Stripping is affected by the type of chemical used (some are absorbed more than others on to the sheep's skin and wool

grease), and also by wool length and dip fouling and the presence of dip sludge (see below). Consequently, additional ectoparasiticide concentrate and water need to be added at intervals to maintain the original ectoparasiticide concentration and the dipwash volume (Fig. 9.1). This can be achieved by one of three methods – 'reinforcement', 'topping up' or 'replenishment', each of these terms describing a slightly different approach. Stripping of dipwash is more marked in the early stages of dipping, but tends to stabilize at a certain level as dipping progresses, and varies again after the dipwash has been replenished (Cook and Wallace, 1974).

1. *Reinforcement.* The addition of ectoparasiticide concentrate at frequent intervals to maintain the concentration in the bath at a relatively high level.
2. *Topping up.* The addition of made-up dipwash at the original concentration to maintain volume.
3. *Replenishment.* For non-stripping dips (those that are less absorbed by the sheep), the wash is replenished with wash (concentrate and water) at the same (original) concentration and there is no need to wait for a specific drop in volume or a specified number of sheep so the operation can be carried out when convenient (as long as there is enough dipwash to adequately immerse the sheep).

For stripping dips, dipwash (i.e. ectoparasiticide and water) is added at an increased concentration to compensate for stripping. This is the commonest method used and can be carried out in three ways: (i) 'intermittent replenishment' (IR); (ii) 'continuous replenishment' (CR) – which is also used for non-stripping dips; or (iii) 'constant dose replenishment' (CDR), as described below. Plunge-dip formulations are only licensed according to the method of replenishment described on the label. Poor or inefficient dipping can not only reduce the efficacy of a plunge-dip formulation to control scab mites (*P. ovis*) and other ectoparasites, but the surviving mites, exposed to sublethal concentrations of active ingredient, may develop ectoparasiticide resistance. Plunge dipping itself is not foolproof and attention to detail is extremely important.

Intermittent replenishment (IR). IR is the addition of diluted concentrate, traditionally at 1.5 times the initial concentration, at intervals throughout the dipping operation, to maintain the dipwash above the maintenance level. IR can be after a drop in dipwash volume (with the required drop in dipwash volume (e.g. 10%) recorded on the side of the dip tank or on a graduated stick while calibrating the dip bath) or after a defined number of sheep have been dipped (head count method).

Continuous replenishment (CR). CR (continuous – or constant – replenishment) involves the addition of clean, made-up dipwash at the initial concentration continuously

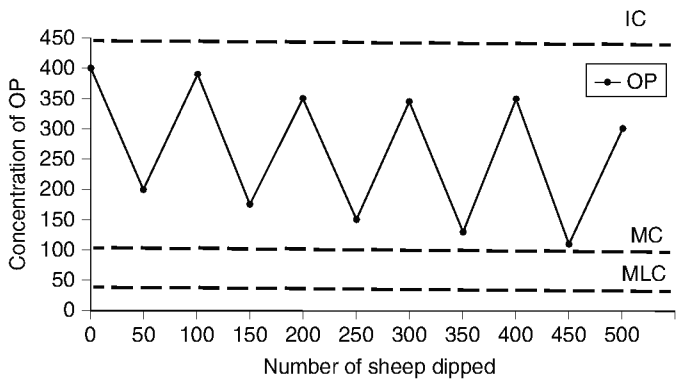

Fig. 9.1. Depletion of ectoparasiticide (the organophosphate (OP) diazinon) with time following plunge dipping (IC, initial make-up concentration; MC, maintenance concentration; MLC, minimum lethal concentration).

throughout the dipping operation. This method can be used for non-stripping dips, in which the concentration in the bath is the same throughout dipping. All that is required is that there is enough actual dipwash in the bath to immerse the sheep.

In Australia, CR is considered to be the best method for stripping dips as well. A supply tank next to the dip bath runs fresh wash at a constant rate. The concentration is the supply tank is usually at a higher concentration than the initial charge in the dip tank, which allows for replenishment and reinforcement at the same time.

The advantages of CR include:

- Reduced fluctuation in the concentration of dipwash.
- No interruption in the flow of dipping to replenish and reinforce the dip.
- More efficient use of chemical as replenishment requires that the concentration is often higher than necessary at the start to ensure that it will be sufficient when the concentration falls before the next reinforcement.

Constant dose replenishment (CDR). CDR is similar to CR and combines both the head count method and the drop-in-volume methods of intermittent replenishment. Sufficient ectoparasiticide and water are added to and taken out of the dip bath as each sheep is dipped. This is achieved by a device (manual or automatic) set up by the side of the dip. The initial concentration of dipwash is made up in the normal way and the machine is set running to deliver its standard dose per sheep. Ectoparasiticide concentration will fall steadily and can fall well below the maintenance level. Approximately 200 sheep are dipped before the concentration equilibrates. This equilibrium shows that each sheep is taking out the equivalent of what the device puts in. This is in fact equivalent to replenishing after a drop in volume caused by one sheep.

DIPPING OUT. Dipping out involves allowing the dipwash level to fall without topping up as usual when the last group of sheep is being dipped, or before cleaning out the dip bath. To determine when to start dipping out, an estimate is made of the rate at which the wash is being removed from the dip. Then a calculation is made of how many sheep will take the dip bath to half its initial volume. The dip bath is kept at full volume until that number of sheep remains, then dipping out is begun. When the dip bath falls to three-quarters of its initial volume, the dip is reinforced, but no water is added. Dipping out is continued until the dip bath reaches half of its initial volume, then dipping is stopped and the bath cleaned. The dip bath volume should never be low enough to allow sheep to walk in the dip and not become properly immersed.

Formulations of ectoparasiticide vary throughout the world. Dipping out is widely used for Australian and New Zealand plunge-dipping formulations, but is not advised for the plunge-dipping formulations available in the UK.

VARIABILITY IN ECTOPARASITICIDE UPTAKE IN THE FLEECE/SKIN. Throughout plunge dipping, the amount of ectoparasiticide deposited on sheep is not constant (Cook and Wallace, 1974). Field studies investigating the depletion of the OP diazinon at six supervised field dippings in Britain that involved a total of 4660, mainly open-fleeced hill breeds (Swaledale or Scottish Blackface) have shown that the uptake and retention of ectoparasiticide in the fleece can show great variation between individual sheep. This variation can be so great that levels on some sheep on day 0 can be lower than the levels on other sheep 28 or 56 days after dipping. The lowest individual fleece levels for sheep dipped in either a 5% or 60% diazinon formulation, sampled on day 0 were 71 mg/l (fleece length of 9.0 cm) and 868 mg/l (fleece length 3.5 cm), and were equal to the mean value for the remaining 29 sheep in the study groups 35 or 40 days after dipping, respectively.

CALCULATION OF DIP-TANK CAPACITY. The exact volume of the dip tank (dip bath) must be accurately calculated, preferably on the day of dipping. Volume can be measured by adding known volumes of water from a measured

container, by using a water meter, or by calculation (see Appendix).

MIXING THE DIPWASH. Effective mixing of the dipwash, both initially and at replenishment, is essential. In New Zealand, it is recommended that the first 20–30 sheep are used to help mix the dip. These sheep should be re-dipped later. Mixing is very important, and with an EC formulation the initial charge may not be mixed thoroughly until the first 10–290 sheep have been through the wash, despite mixing by hand.

EFFECTS OF RAIN. It is advised not to dip wet sheep. Traditionally, it was believed that the fleece would not absorb any more moisture, and, therefore, any more ectoparasiticide. Field and laboratory studies have shown no connection between the degree of fleece moisture before dipping and uptake of ectoparasiticide in the fleece (Bates, unpublished data). Most sheep dips have a high affinity for wool grease, and this uptake takes place in the dip bath (Bates, unpublished data), and not through sieving out while in the draining pen. Conversely wet sheep can add water to the dipwash, causing complications relating to the drop in volume form of replenishment. In such cases, the dip bath volume drops slowly yet the ectoparasiticide concentration drops rapidly, and later sheep could be dipped in lower concentrations of ectoparasiticide at or below the MLC.

Heavy or light rain within 3 weeks of dipping can wash out 8% or 12% diazinon, respectively, or 28% of propetamphos from the fleece over 3 weeks compared with indoor controls. In sheep that are washed or bloom dipped (cosmetically dipped for showing) within 2 weeks of dipping in ectoparasiticide, the fleece ectoparasiticide concentration can be seriously reduced.

FLEECE STAPLE LENGTH. A compulsory national summer dipping for sheep scab mite (*P. ovis*) infestation was introduced in the UK in 1982. One reason behind this policy was that fleece would be shorter and therefore allow for easier penetration of the dipwash to skin level and with reduced depletion.

There appears to be a relationship between the length of fleece staple and the uptake of ectoparasiticide. The shorter the fleece, the greater the ectoparasiticide uptake. In fact, shorn fleece 1.0 cm in length holds the same concentration of ectoparasiticide weight for weight as a full staple (Kirkwood, personal communication), but in the shorter fleece the active ingredient is diluted along the wool staple as it grows. Dipping shorn lowland sheep (Dorset Horn or Suffolk cross hoggs with 1.0 cm fleece) in 5% or 60% formulations of diazinon or in an 8% formulation of propetamphos resulted in 28%, 0.8% and 13% more ectoparasiticide compared with full-fleeced sheep, respectively. Fleece ectoparasiticide levels in sheep dipped in the non-tripping SP flumethrin demonstrated little difference, with 41.5 mg/l recorded in fleece of 9.0 cm length and 51.7 mg/l in fleece of 12.8 cm length. A fleece length of at least 1.0 cm is essential for effective plunge dipping, and the rigidity of the compulsory dipping periods in the UK often caused problems. During the Scab Eradication Campaign, delayed shearing due to bad weather often meant that sheep could be dipped directly after shearing or shorn after dipping. Summer dipping was considered to be a curative dip, killing over-summering populations of *P. ovis*. A fleece length of 1.0 cm can only guarantee protection against reinfestation for 3 weeks because the active ingredient is soon diluted as the fleece grows (at a rate of approximately 1.0 cm/month). Winter dipping not only cures scab but also gives considerably longer periods of protection.

In New Zealand, it is recommended that sheep should be plunge dipped 3–4 weeks following shearing for effective louse (*B. ovis*) control. The minimum interval off-shear is 2 weeks, which gives a chance for shearing cuts to heal. The maximum interval off-shear is 8 weeks for fine wool and 12 weeks for strong wool.

SHEEP BREED. There appear to be no clear differences in the uptake of a 60% diazinon formulation between an open-fleeced hill breed (such as Scottish Blackface) and a

close-fleeced lowland breed (such as Dorset Horn). In New Zealand, Clear *et al.* (1982) demonstrated that there was no statistical difference in diazinon levels, wool yield or grease content between the Romney and Drysdale sheep breeds. However, weights of wool grease do vary between breeds of sheep. Merino fleece has been shown to have 15–20% wool grease, whereas Romney and Romney Cross fleeces have 8–10% (Cook and Wallace, 1974). The merino fleece may absorb more ectoparasiticide than the Romney fleece. Diazinon yield and grease content for goat hair differ significantly from those for sheep fleece.

WOOL GREASE AND SUINT CONTENT. No published data are currently available, but it is safe to assume that months when the wool grease is high are months when the uptake of dip is greatest. In New Zealand, seasonal differences in the persistence of sheep dip ectoparasiticide have been demonstrated, with sheep dipped in May having increased periods of protection against blowfly strike than those dipped in December to February. During the initial stages of the plunge-dipping operation, there is no suint (the water soluble fraction of wool grease) in the dipwash. In New Zealand, it is suggested that the lack of suint in the dipwash makes the first few batches of sheep harder to wet. It is therefore recommended that the first two or three batches of sheep are re-dipped later in the day.

ECTOPARASITICIDE CONCENTRATION IN THE DIP BATH. There is a relationship between dipwash ectoparasiticide concentration and fleece uptake. This is dependent on the type of active ingredient, the formulation and the method of replenishment. Intermittently replenished diazinon dipwash shows a rise in ectoparasiticide uptake proportional to an increase in dipwash concentration. Nix (personal communication) also observed (through *in vitro* studies) that the concentration of diazinon taken up increased with that of the dipwash, but became proportionally less above 100 mg/l in the wash. Increasing the concentrations of OP ectoparasiticides in the dipwash does not give proportionally increased protection against blowfly strike. A point of maximum absorption is reached.

The amount of OP ectoparasiticide absorbed on to the wool grease is considerably more than that simultaneously recorded in the dipwash. For a stripping formulation of 60% diazinon the dipwash concentration may be 276 mg/l but the fleece loading will be 3189 mg/l. Thus, fleece concentrates the active ingredient, with approximately ten times more diazinon in the fleece than in the dipwash. This relationship does not hold true for a non-stripping SP formulation, where a 6% flumethrin dipwash concentration may have 63.3 mg/l flumethrin and the fleece loading may be 48.5 mg/l.

TIME OF IMMERSION. Although 30 s is adequate for the control of other ectoparasites (e.g. blowflies), 60 s is the only acceptable time to ensure the saturation necessary to kill the scab mite, *P. ovis*. Dipping for less than 60 s allows a 60% failure in both cure and protection against scab. Sheep dipped for 40 or 20 s could take out 38% or 50% less ectoparasiticide, respectively, than those dipped for 60 s (Kirkwood, personal communication). In unsupervised dippings, sheep may only be immersed for 10 or 15 s.

Timing is usually carried out using a stop clock, but can also be calculated by the time it takes sheep to swim through the dip bath, particularly in long swim through and circular baths. In Australia and New Zealand, this is achieved through having a minimum length of 9 m for a long swim bath, giving a minimum time of 20 s to swim the length of the dip and allowing for two required head dunks. In all dip baths, sheep must be kept moving: the swimming action displaces the air in the fleece, thus aiding dipwash penetration. In short swim dips the sheep may need to be actively held back to keep them in the dip bath long enough to achieve adequate saturation. The flow of sheep into the dip must be regulated. If sheep pile up in the dip it slows down the whole operation and prevents some sheep being dipped correctly. Some sheep may stay on the top of other sheep and do not get fully immersed. Even if the head is immersed correctly, dipwash does not penetrate the

ear canal completely and mites in the ears can survive dipping; in such cases, their exposure to sublethal concentrations of acaricide could select for resistance.

FOULING OF THE DIP BATH. As sheep pass through the dipwash it becomes progressively fouled with organic matter such as soil, faeces, fleece, kemp, etc., and the physical state and composition of the dipwash changes as dipping progresses. Badly fouled dipwash reduces the amount of ectoparasiticide available to the sheep, as the organic matter provides a substrate for the absorption of ectoparasiticide so that there is a partition between fleece and organic matter which renders the active ingredient unavailable to the fleece. This situation is circumvented by replenishing with dipwash at a higher concentration of ectoparasiticide. It is not unusual for a dip bath to be fouled by 3–5% organic matter at the end of dipping. Fouling of 5% can lead to 60% less fleece uptake compared with that from clean dipwash (Bates, unpublished data).

Because of this fouling, the entire dipwash should be discarded after one sheep–1.5 l (three sheep–gallon) of the initial volume of dipwash have been dipped (i.e. after 600 sheep for 200 gal or 900 l of dipwash). Disinfectants can be added to the wash at the end of a day's dipping (according to the manufacturer's instructions), which allows dipping to continue the next day, but some dipwash (e.g. flumethrin) is still effective 14 days after making up. This allows stragglers to be dipped without the problems and expense of making up a fresh wash, although there is always the potential that dirty dip can spread diseases such as post-dipping lameness. The manufacturer's instructions must be followed at all times.

Fouling can be reduced by cleaning the dip bath before use and dagging all sheep before dipping. Races leading to the dip entry should be made of rough concrete or slats to remove dirt/faeces from the feet. All filter screens, dip enclosures, forcing/draining pens should be cleaned before dipping. Throughout dipping, the collecting and draining pens must be swept regularly and kemp, fleece and faeces skimmed off before each replenishment.

WATER QUALITY. Studies at the VLA have suggested that factors such as water quality, particularly high salinity or hardness, can destabilize large proportions of an EC dip formulation, and so affect the concentration of ectoparasiticide in the dip bath.

DEGRADATION OF FLEECE ECTOPARASITICIDE WITH TIME. As soon as the ectoparasiticide is absorbed into the wool or skin grease it begins to break down (degrade), with the highest concentrations occurring within the first few weeks of dipping. Although shorn sheep (with 1.0–3.0 cm of fleece) take out more ectoparasiticide initially, the rate of degradation in the fleece is quicker, with 35–51% retained 28 days after dipping compared with 53–77% for unshorn sheep. However, 56 days after dipping, the values are almost equal ranging from 26% to 28% for diazinon (Bates, unpublished data) (Table 9.1).

There are many reasons for the degradation of ectoparasiticide in the fleece. Mechanical detachment may be responsible for the degradation of formulations of aldrin. Studies in New Zealand by Rammell and Bentley (1990) demonstrated that decay rates for five OP dip formulations varied with the season, the area of the fleece sampled and the ectoparasiticide formulation. The time taken to reach a given OP level in autumn/winter was 2.7 times that taken in the summer. Differences in fleece length and wool grease content were not sufficient to account for the differences. Shorter summer half-lives with the higher flux of UV light and higher ambient temperatures are more likely causes.

Table 9.1. Relative uptake and depletion of ectoparasiticide after plunge dipping shorn or unshorn sheep in a diazinon dipwash (Source: Bates, unpublished data).

	Ectoparasiticide retained in fleece (%)			
	Days post-dipping			
Dip formulation	28		56	
	Shorn	Unshorn	Shorn	Unshorn
60% diazinon	35	53	28	27
5% diazinon	51	77	26	28

The atmosphere effectively absorbs UV light shorter than 290nm, but sufficient energy exists within the range of solar UV (290–400nm) to induce chemical transformation of OP ectoparasiticides. Rammell and Bentley (1990) also recorded faster decay rates on the back of the sheep than on the flanks.

DIFFUSION DOWN THE FLEECE STAPLE TO SKIN LEVEL. Ectoparasiticides also diffuse down the wool staple with time. Fiedler and DuToit (1954) described the movement of ectoparasiticide down the wool fibre by diffusion through the wool grease, until it eventually reached the new wool growth next to the skin. Studies at the VLA have shown similar results, with the relative proportions of ectoparasiticide in the top, middle, lower and recent growth sections of the wool staple remaining constantly proportional with time (Kirkwood, personal communication) (Table 9.2). New wool growth arising from the skin follicles continuously absorbs ectoparasiticide, and so ectoparasites living close to the skin (e.g. mange mites and chewing lice) can be exposed (for a time) to fresh ectoparasiticide.

Little information is available on the actual ectoparasiticide concentrations in the fleece at skin level (i.e. in direct contact with the sheep scab mite *P. ovis* at the point of breakdown in ectoparasiticide activity). The mean fleece ectoparasiticide concentrations for sheep dipped in either 100mg/l diazinon (the maintenance level for this ectoparasiticide) or 50 and 30mg/l diazinon were between 145 and 200mg/l at skin level for all concentrations. One of the criteria for recommending a sheep dip formulation for a product licence for efficacy against sheep scab is that by following the manufacturer's instructions for replenishment, the dipwash ectoparasiticide concentration will never fall below the maintenance level at which the formulation is guaranteed to give a clear 3 weeks protection on shorn sheep and complete cure in infested sheep. For the 60% diazinon formulation, this level of protection/cure can be extended to state that it can be achieved as long as an ectoparasiticide concentration of 145mg/l or above exists in the fleece at skin level.

Table 9.2. Diffusion of diazinon down the fleece staple following plunge dipping (Source: Kirkwood, personal communication).

	Time post-dipping (weeks)		
	5	10	15
Fleece length (cm)	7.6	12.5	16.0
Wool staple zone			
Top%	19.6	10.6	13.6
Middle%	31.6	30.0	31.1
Lower%	26.7	34.6	36.2
Recent%	22.0	24.0	18.8
Total (mg/l)	2396	1349	609

VARIATIONS DUE TO BODY AREA. The uptake of ectoparasiticide on a sheep is not uniform and varies considerably with different parts of the fleece. Fine-quality areas of wool (shoulders to mid-back) have been shown to retain more aldrin than coarser area of wool (the tail-head, hind legs and lower flanks). Kirkwood *et al.* (1978) analysed wool from different parts of the sheep for diazinon concentration with time, and showed that some areas took up more ectoparasiticide than others, namely (in order of magnitude) the brisket, side, back and abdomen; diazinon on the abdomen was the quickest to degrade.

PROTECTION AGAINST (RE)INFESTATION. Scab mites (*P. ovis*) and chewing lice (*B. ovis*) can live off the host and remain infestive to other sheep for 15–17 days (O'Brien *et al.*, 1994; Morcombe *et al.*, 1994). All diazinon-based plunge-dip formulations are guaranteed to protect against *P. ovis* for at least 3 weeks on sheep with 1.0cm of fleece. In reality, this would be considerably longer on full-fleeced sheep. Consequently, these sheep can be returned to an infested pasture, yard or barn directly after dipping, without risk of reinfestation.

DANGERS OF PLUNGE DIPPING.

Effects on production. Experimental studies have demonstrated that plunge dipping has no significant effects on mating, conception, gestation and lambing performance.

Increased susceptiblility to other fleece/skin infections. Wetting the fleece and holding wet sheep can increase the risk of other skin conditions, including mycotic dermatitis (*Dermatophilus congolensis*), 'fleece rot' (*Pseudomonas aeruginosa*), 'cheesy gland' (caseouslymphadenitis),tetanus(*Clostridium tetani*) and 'pink eye' (*Moraxella bovis*). The stress of dipping can lead to pregnancy toxaemia, hypothermia, mis-mothering, drowning and trampling.

Post-dipping lameness (PDL). Post-dipping lameness (PDL) is a non-suppurative cellulitis, primarily as a result of infection of the coronary band of ewes and lambs by *Erysipolothrix rhusiopathiae*. In its typical form, PDL presents as a sudden outbreak of lameness in sheep dipped in the previous 2–5 days, with up to 80% of animals affected (Lamont, 1988). PDL was first reported in Australia and New Zealand in the 1940s and was subsequently reported in the UK and South Africa. The sudden advent in PDL was blamed on the introduction of lindane-based dip formulations, which lacked the inherent bactericidal activity of the tar/phenolic-based dipping formulations (Lamont, 1988). PDL could be prevented by the addition of copper sulfate to the lindane dipwash. PDL re-emerged in the UK in the 1970s following the introduction of the OP (diazinon) dip formulations. The development of OP-compatible bacteriostats/bactericides and improved dipping procedures brought PDL under control (Lamont, 1988).

Subcutaneous swellings. Sargison *et al.* (1995a) reported large subcutaneous fluid swellings on sheep in two flocks infested with *P. ovis* during the 2 weeks after they had been plunge dipped in a phenol-based solution. The swellings contained 1–10l of exudate and affected 4% of sheep in each flock. The sheep with subcutaneous fluid swellings or exudative dermatitis had significantly lower serum albumin concentrations than the unaffected sheep. In most cases, secondary bacterial infections of the exudate occurred and these required intensive antibiotic therapy. The severity of the skin lesions was considered to be a serious welfare problem.

THE FUTURE OF PLUNGE DIPPING. Plunge dipping sheep in baths of ectoparasiticide has been the most effective method of sheep ectoparasite control throughout the world for over two centuries, but its problems are multifactorial. To the operator, it is time-consuming and labour intensive, and OP formulations have been incriminated in post-dipping illness. For the environment, residues in the fleece and the disposal of large volumes of used dipwash pose considerable problems. The operator safety issues and ecotoxicity of plunge dipping and plunge-dipping formulations, and the introduction of safer, less labour-intensive methods of ectoparasiticide application have meant that these newer methods have largely superseded plunge dipping for ectoparasite control throughout the world. In Argentina, the availability of over 40 relatively cheaper, generic, ivermectin-based products means that the use of these has surpassed plunge dipping in popularity, which poses a high risk of selection for ivermectin resistance. Many farmers have now broken up their dipping facilities, and rely solely on the use of MLs. In the UK and South Africa, there is an increasing problem with chewing lice (*B. ovis*) as a result of the sole use of endectocides for scab control.

Shower dipping

Shower dipping was first used in New Zealand in 1905, and has been used for louse and blowfly control in Australia and New Zealand since the 1950s. It is regaining popularity as SP pour-ons lose their efficacy against chewing lice (*B. ovis*) (Levot, 1992). Following the deregulation of sheep scab as a notifiable disease in the UK in 1992, there was an increase in the use of mechanical methods (e.g. shower dips and AJRs) for the application of ectoparasiticides to control lice, blowflies and sheep scab mites (*P. ovis*) (Bates, 1999d). Sheep scab was eradicated from Australia in 1896 and from New Zealand in 1885; consequently, there is little information on the efficacy of ectoparasiticides administered via shower dips to control scab.

The advantages of shower dipping over plunge dipping include:

- It is more 'eco-friendly', using less dipwash (and therefore there is less wash to dispose of).
- More animals can be treated at a time.
- Showers are semi-mobile (and thus can be sited away from water courses).
- It is less labour intensive.

The disadvantages of shower dipping include:

- There is a high initial cost of equipment.
- The shower dips are difficult to maintain in effective working order.
- It is difficult to detect equipment problems, resulting in some sheep not being fully saturated.
- Sheep must be remustered a few weeks after shearing, with an increased risk of missing sheep and extra labour input.
- Sheep that miss remuster and treatment cannot be readily identified.
- There is a risk of wound infection or deaths due to cold exposure.
- There is a high human safety risk due to spray from the dip.

These factors are summarized in Table 9.3.

EQUIPMENT. Shower dips submit sheep to a deluge of ectoparasiticide wash, the aim being to soak the entire fleece to skin level. The basic principles of plunge dipping, particularly the IC, ML and MLC of the ectoparasiticide, all apply to shower dipping. Similarly, the theories and practices of replenishment, topping up and reinforcement also apply.

Shower dips generally consist of a circular (or rectangular) enclosure into which sheep are herded and showered. Fixed sprays on the floor wet the underside of the sheep, but the majority of saturation is achieved by nozzles attached to a horizontal boom above the sheep, which rotates about a central pivot. Ectoparasiticide is pumped at a high rate (e.g. 400 l/min) from a sump and through the nozzles, and excess wash runoff is drained into the sump and recycled. Circular shower dips are considered more effective than rectangular dips. In Australia and New Zealand, most shower dips are static, holding 30–50 sheep (Fig. 9.2). In the UK, shower dips are generally lorry mounted and mobile and hold only 10–15 sheep (depending on size) (Fig. 9.3).

The degree of wetting achieved is an important factor in the control of lice and other ectoparasites (Higgs *et al.*, 1994); this, in turn, is a factor dependent on the mechanical performance of the shower, particularly the volume, pressure, and spray pattern and distribution (Lund *et al.*, 1996).

Table 9.3. Advantages and disadvantages of plunge and shower dipping.

	Plunge dipping	Shower dipping
1	Ease of wetting	Attention to detail required
2	Low maintenance of equipment	High-maintenance equipment
3	Static – sheep need to taken to the dip bath	Can be mobile – the dip bath can be taken to the sheep
4	Attention needed in mixing	Easy to mix evenly
5	More chemical used	More efficient and economic
6	More water required	Less water required
7	Relatively large volumes of used dipwash to dispose of	Relatively little used dipwash to dispose of
8	Less hygienic	Lower possibility for disease transmission
9	Labour intensive	Less labour required
10	Less skill required	Skill and attention to detail essential
11	Smaller numbers of sheep can be treated in one batch	Larger numbers of sheep can be treated in one batch
12	More chemical in the environment	Less chemical in the environment
13	Effective against sheep scab	Not effective against sheep scab

FACTORS AFFECTING EFFICACY. Lice (*B. ovis*) live close to the skin. Consequently, they will only be killed if the sheep are saturated to skin level. The inherent problem is that one of the functions of a full fleece is to prevent the sheep getting wet during the winter, so it is extremely difficult to wet a full-fleeced sheep to skin level.

Fig. 9.2. An Australian shower dip (Photo © P. Bates).

CALCULATION OF DIP CAPACITY. The sump capacity must be calculated to allow the correct concentration of dipwash to be maintained. With constant replenishment systems, the supply tank should be calibrated and the calibrations marked on the tank or a dipstick prepared for the tank.

MECHANICAL CONSIDERATIONS. The majority of the efficacy factors discussed for plunge dipping also apply to shower dipping. In addition, shower dipping relies on the mechanical performance (volume, pressure, spray pattern and distribution; Palmer and Lund, 1996) of the shower dip itself. Also, reliance may be placed on complex machinery that may never have been appropriate for the task, and there may be poorly understood management of ectoparasiticide strength during dipping (Levot *et al.*, 1995; Sinclair, 1995).

The top rotating boom of the spray must be centred and level, ensuring that dipwash is sprayed evenly on the backs of all sheep. The arm should rotate at approximately five revolutions per minute (rpm). High speeds of above 12 rpm do not wet sheep thoroughly.

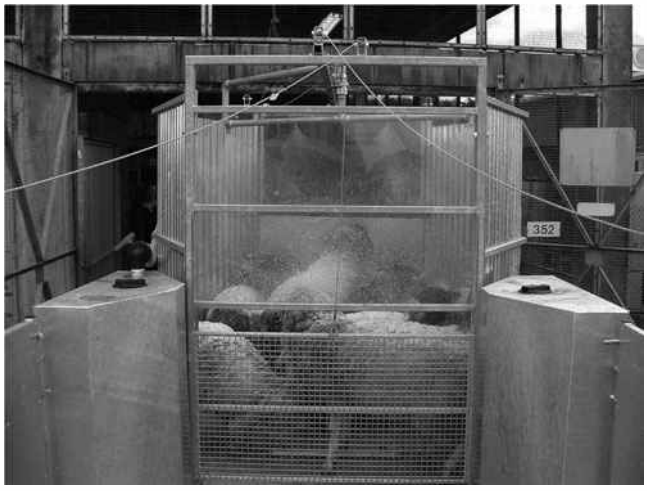

Fig. 9.3. A British (monsoon type) shower dip (Photo © P. Bates).

The speed can be changed by altering the angle (typically 26–28°) of the terminal (driving) nozzle. Increasing the angle increases the speed. All other nozzles on the boom should face directly downwards. Also, all nozzles, particularly those on the rotating boom, must be clean and ideally have one long slit. Nozzles with many small openings are not effective and should be replaced. Bottom sprays do not wet the sheep any better than using the top sprays alone and are a major cause of spray drift; their use is not recommended.

PUMP PRESSURE AND NOZZLES. One of the most important factors affecting sheep wetting is the volume of dipwash delivered from the nozzles. This can be determined by pump pressure, the diameter of delivery pipes and the spray nozzles. The pump should supply at least 390 kPa to achieve above 230 kPa at the spray nozzles. Some producers modify their shower dips with higher diameter pipes to increase the volume of dipwash delivered. Overhead nozzles should spray to the side walls at just above sheep height. If the spray does not reach evenly up the walls of a circular dip, then the pivoting point of the spray may be off centre.

The flow rate and pump pressure can be checked by a bucket placed anywhere on the floor of the dip, which should fill at a rate of 2 l/min. Common causes of low pressure include worn impellors in the pump or low pump speed. A rough guide to the correct pressure is that the bottom jets should reach 30–40 cm above the top of the dip when run alone. All nozzles, pipes, valves and sieves must be clean and working.

MIXING THE DIPWASH. Many dipping chemicals are in a form that does not readily disperse if poured directly into a large volume of water, and rather settles to the bottom. Premixing in a bucket will disperse the concentrate in a form that will mix more readily in the tank. Dipwash should be mixed thoroughly with a paddle and then by running the top sprays in an empty shower dip for 3 min. It is important to repeat mixing after any break of an hour or longer as some mixtures may settle on standing.

Fresh unused dipwash has poor wetting properties, owing to the lack of suint, which improves wetting. In Australia and New Zealand, it is customary therefore to return the first 30 sheep to the shower. This will also improve chemical mixing of the dipwash.

SHOWER DIP FORMULATIONS. In Australia and New Zealand, there are specific formulations for use in shower dips. In the UK, users of shower dips rely on OP plunge-dip formulations which are readily purchased over the counter. It is not an offence to apply plunge-dip formulations through such mechanical devices, although such formulations are only authorized for use according to the instructions detailed by the manufacturer (i.e. as a plunge dip). The behaviour of the currently authorized OP plunge-dip formulations through mechanical devices such as shower dips is still relatively unknown. It is not known whether plunge-dip formulations deplete in a similar manner when applied via showers or sprays, and therefore require the same replenishment rates. There is also little available information concerning the curative or protective efficacies of these formulations when applied other than by plunge dipping. Nor is there any available information on their human/environmental safety. Thus, the user in the UK takes full responsibility for any adverse reactions and/or lack of efficacy that may result.

LOADING THE SHOWER DIP. It is important not to pack sheep too tightly in a shower, they must be touching but still able to move. Lambs should be dipped separately to be properly wetted and avoid trampling. Sheep tend to gather around the exit gate, and it is important to cover the gate in the same material as the walls of the dip. Covering the gate during dipping is safer for the sheep and improves wetting.

TIMING AND FLEECE LENGTH. There is no correct time for sheep to remain in the shower dip. Saturation time should be adjusted depending on wool length, body size, breed and the efficacy of the shower, to ensure that the sheep are sufficiently wet at skin level.

Groups of sheep within the shower dip must be of uniform size and fleece length, and should be able to move around freely. The degree of wetting can be monitored using an indelible pen. Once a suitable time is established, this can be used for consistency.

Breeds with open wool are easier to wet than those with fine wool. Fleece length is an important limiting factor in relation to dipwash penetration to skin level. It is impossible to thoroughly wet sheep with more than 6 weeks of wool growth; the shorter the fleece, the easier it is to saturate to skin level.

Dipping off-shears is not recommended because of the increased risk of infection in shearing cuts. If cuts are a problem and off-shears have to be shower dipped, then a disinfectant should be added to the dipwash and close attention paid to keeping the sump clean. Off-shears should be showered for 5–6 min (4 min from the top and 1–2 min from the bottom). Sheep with 2–4 weeks of wool growth should be showered for longer. It has been stated that sheep should be showered for a minimum of 8 min (6 min from the top jets and 2 min from the bottom jets). Sheep with more than 6 weeks of wool growth are very difficult to wet properly, will take longer to dry and are more prone to fleece rot, mycotic dermatitis and death from cold stress. Ten days off-shears is the minimum time, enabling good wetting and allowing time for any shearing cuts to heal.

Tufts of wool left after poor shearing are hard to wet and it is important that sheep are wet in neck folds (particularly merinos) and that rams are wet under the horns. It may be necessary to draft off the sheep that will be hard to wet so that they can be dipped separately, and given more time and attention in order to facilitate thorough wetting.

CONSTANT REPLENISHMENT. Most shower dip set-ups are of the CR type in which wash is pumped from a small capacity (1500–2000 l) underground sump that is constantly replenished with fresh dipwash from a large (2000–5000 l) supply tank (Cook and Wallace, 1974). There is still a drop in wash concentration, but better stabilization is achieved by this method. Because the sump is kept topped up the dipping operation is cleaner and the concentration of the dipwash is kept relatively constant. The supply tank must be kept running; failure to do so will result in rapid, heavy exhaustion of the wash and sheep showered at that time will receive inadequate deposits of ectoparasiticide (Cook and Wallace, 1974).

The dipwash becomes contaminated owing to recycling of the mixture, so the sump must be emptied regularly, discarding all dipwash. This should be carried out after dipping one sheep for every 2 l of initial sump volume (e.g. 500 sheep can be dipped for a 1000 l sump before the sump needs to be emptied and cleaned). In Australia and New Zealand, it is common practice to use the wash remaining in the sump to treat the last few pens of sheep (dipping out). As 30–50 sheep are treated at a time, this mistake could result in over 100 sheep being showered in 'dirty water', making them more susceptible to blowfly strike (Cook and Wallace, 1974).

DIPWASH FOULING. As in plunge dipping, the dipwash must be kept relatively clean. Ectoparasiticides bind to soil and faeces in fouled dip, and adding more chemical will not overcome this problem.

VARIATIONS IN ECTOPARASITICIDE UPTAKE WITH BODY AREA. Shower dipping does not saturate to skin level over the entire body, despite long exposures, and shower dips are only effective if they thoroughly wet (enough of) the sheep to skin level with an adequate concentration of an effective dip chemical. Rams can be harder to wet, particularly under the horns and on the neck. Sheep with heavy neck folds (typical of the Australian merino breed), poorly shorn animals and sheep affected by 'lumpy wool' or fly strike are also harder to wet, and these animals should be treated separately.

The bulk of the wetting is achieved by nozzles attached to the horizontal boom above the sheep, as it rotates around a central pivot (Palmer and Lund, 1996). Wash that falls on the fleece in a direction other

than parallel to the fibres tends to flow around the exterior of the fleece until it drains off the ventral surfaces. This wash will not penetrate the fleece to any degree, and usually just wets the tip of the staple. Wash that falls on the midline of the back penetrates beneath the wool staples to saturate the skin, reaching the ventral surfaces by gravity and not from the floor jets (Sinclair, 1965). Kirkwood *et al.* (1978) observed that 75% of the wash present on the ventral surfaces gravitates from above. Wash forced up from the floor jets is usually in droplets and only wets the tip of the belly wool (Sinclair, 1965). Higher levels of ectoparasiticide are found in the wool/skin on the back, with lower concentrations on the ventral surfaces, especially the crutch (Kirkwood *et al.*, 1978).

SHOWER DIPPING VERSUS PLUNGE DIPPING. Sheep are more saturated via plunge dipping than by shower dipping. Studies have shown that 36 mg/l and 410 mg/l diazinon on the underside of showered sheep compared with 336 mg/l and 6960 mg/l on the underside of dipped sheep (Kirkwood *et al.*, 1978). Also, plunge dipping for 1.0 min fully saturates the fleece, all over the sheep, to skin level. Neither is shower dipping necessarily the most economic method of applying dipwash to sheep. Kirkwood *et al.* (1978) estimated that 9.6 l of wash per sheep was required for shower dipping, compared with only 2.4 l per plunge-dipped sheep.

Differences in the efficacy of shower and plunge dipping are due to two factors: (i) the need to keep the fleece open (so that air between the wool fibres is easily replaced by insecticide; and (ii) the need to penetrate not only the wool but also the skin and, for sheep scab, the cryptic sites (the inside of the ears, infra-orbital and inguinal fossae, and the crutch). Plunge dipping accomplishes both of these aims (Kirkwood *et al.*, 1978, 1983). The fleece is not compressed but remains extended, with the fibres floating free, thus allowing for air to be displaced by wash. Active, vigorous swimming of the sheep will actively work wash into the cryptic sites (Kirkwood *et al.*, 1978). Analysis of the diazinon content of the fleece of the crutch of showered sheep demonstrated that this was much less than that of plunge-dipped sheep, 56 mg/l compared with 336 mg/l, respectively (Kirkwood *et al.*, 1978).

RESISTANCE ISSUES. The exposure of scab mites (*P. ovis*) to sublethal concentrations of ectoparasiticide via ineffective administration using mechanical (shower) devices may select for resistance to the plunge-dip formulations themselves.

Automatic jetting races (AJRs)

AJRs rely on spraying dipwash under high pressure on to the sheep, thus ensuring good fleece penetration. The low volumes used minimize drip loss from sheep and therefore run off (and are possibly safer for the environment). In Australia, jetting is used to apply ectoparasiticide to the backline, crutch and pizzle areas of the sheep for the prevention of blowfly strike (Lund and Kelly, 1994).

The use of AJRs is quicker than hand jetting (see next section), with a throughput of approximately 500+/h recorded. Jetting is less stressful to both sheep and operator, and because of the lower volume of wash used, there is less wash to dispose of. There is also less reluctance for sheep to walk through a jetting race than a dipping bath. However, AJRs have been shown to be less effective than hand jetting (Herdegen *et al.*, 1989); they apply chemical indiscriminately and only achieve limited control against blowfly strike.

As for shower dipping, effective jetting is only achieved by wetting the sheep to skin level in those areas most affected by fly strike – the poll (area between the ears), over the shoulders, down the backline, over the rump and crutch area, and around the pizzle (Lund and Kelly, 2003).

TYPES OF JETTING RACES. There are two general types of AJR (Lund and Kelly, 1994):

- *Continuous* – these spray continuously when the pump can supply the necessary volume at the required

pressure to the spray nozzles (Lund and Kelly, 1994).

- *Intermittent* – sheep activate a valve to turn on sprays as they pass through the race. This imposes different demands on the system, the most important being the reaction time (the time taken for the system to reach steady-state operating conditions after the sheep activates the valve; Lund and Kelly, 1994). Exposure in intermittent races has been calculated to be approximately 1.0 s compared with 2.0 s for continuous races. If the reaction time is slow, inadequate jetting will result, as the system will not reach optimal spray race performance while the sheep are in the race (Lund and Kelly, 1994).

MECHANICAL CONSIDERATIONS. There are a number of underlying principles that need to be understood in order to achieve effective jetting. Work carried out by the Trangie Agricultural Engineering Research Unit (AERU) in New South Wales, Australia determined the optimal requirements for AJRs to run to maximum efficacy; these included spray arrangements, spray characteristics, spray height, volume retained, sheep speed, pipe and valve systems, and pump size (Lund and Kelly, 2003).

SPRAY ARRANGEMENTS. Effective wetting is best achieved if spray nozzles are arranged so that targeted areas of the fleece can be sprayed more than once. This is achieved by positioning multiple spray bars across the flow of the sheep or by using multiple nozzles in line with the sheep flow (Lund and Kelly, 2003). Longitudinal nozzles improve dipwash penetration as successive jets apply dipwash to the same area as the sheep pass through the race. The top spray bars should be arranged in two longitudinal rows, with three to five (5 mm) nozzles, 100 mm apart and adjusted to be 150 mm above the back of the sheep, with the nozzles angled slightly inwards. The bottom spray bars should have three (4 mm) nozzles facing forward at 30°; this improves wetting and reduces operator exposure. One (4 mm) nozzle per side should be situated at knee height and angled upwards and backwards. These 'throat nozzles' improve wetting under the neck, a problem area for AJRs when they are used to control lice. Jetting fluid must strike the fleece as close to parallel to the wool fibre as possible. This will reduce deflection and increase penetration.

SPRAY CHARACTERISTICS. Spray characteristics also influence fluid penetration into the fleece. Good penetration is only achieved with a solid stream. If jets brake into droplets as they leave the nozzles penetration will not be effective (Lund and Kelly, 2003). Misting is generally caused by excessive pressure and/or small jet size.

SPRAY HEIGHT. The further the nozzles are away from the fleece the more the jet stream is likely to break up and so become less effective. Conversely, the closer the nozzles are to the fleece the more effective and efficient the application will become (Lund and Kelly, 2003).

VOLUME RETAINED. The volume of wash retained in the fleece is also important in achieving wetting to skin level; less than optimal volumes will only partially wet the fleece. Sufficient volume needs to be retained so that some wash runs around the body of the sheep. The number of nozzles, nozzle size and operating pressure determine the volume applied over a given time (Lund and Kelly, 2003). Approximately 2.5 l of wash needs to be retained on full-fleeced sheep, and in the appropriate areas, before this can be achieved (Lund and Kelly, 2003). Assuming that offshears are being treated, an absolute minimum of 1.5 l of wash must be applied to each sheep. A significantly larger volume than this is required for short-wool sheep. AJRs that recycle dipwash are not effective.

SHEEP FLOW SPEED. Sheep flow speed through the AJR should allow sufficient time for the necessary volume of spray to be applied. The flow of sheep through the race should be controlled so that the contact time with the nozzles is adequate. A flow of 400–600 sheep/h is considered to be ideal.

With intermittent AJRs sufficient time needs to be allowed for the spray system to adjust to the required operating pressure. The performance of the entrance and exit races adjacent to the AJR are particularly important in controlling sheep flow and speed (Lund and Kelly, 2003).

PIPE AND VALVE SYSTEM. Pipe and valve sizes should minimize pressure losses and thereby improve flow characteristics and minimize pump power requirements. When mechanical operation of the on/off valves varies with sheep size, arrangements should ensure full opening every time (Lund and Kelly, 2003).

PUMP SIZE. The pump must be capable of delivering more than 6 l/s of dipwash with a nozzle pressure greater than 430 kPa. Pump size is specified by its pressure/volume characteristics. The pump's operating pressure is determined by the nozzle requirements and pipe pressure losses. The volume delivered is determined by the nozzles and the sheep speed. To minimize the pump power required, the aforesaid comments about volume retained/applied, sheep speed and pipe and valve system size and arrangements need to be noted (Lund and Kelly, 2003).

Hand jetting

Hand jetting, if carried out correctly, has been shown to be the most thorough method of applying an ectoparasiticide. However, it is relatively slow, hard work that requires good quality, comfortable protective clothing, access to water, a race and proper jetting equipment. The laborious nature of the work, frequently combined with badly designed facilities, can lead to ineffective treatment. Moreover, the thoroughness of jetting diminishes as the operator tires (Levot, 2009c).

Hand jetting thoroughly wets the skin of the sheep by the action of the jetting wand, which is passed along the fleece in a band approximately 25 cm wide from the poll to the tail and in bands on the sides of the neck (Levot, 2009c).

MECHANICAL CONSIDERATIONS.

Jetting sump. The jetting sump should be situated away from the sheep so that its noise during operation does not bother the sheep and inhibit filling of the race (Levot, 2009c).

Pump. The minimum requirement for the pump is the delivery of 30 l/min at 700 kPa (100 psi) to each handpiece (wand) and the return of enough jetting fluid via the recirculating hose to provide sufficient mixing in the sump. A pressure gauge should be fitted in-line at the handpiece to check the pressure. The pump should be checked before use to ensure that it is operating efficiently and adequate fuel should be available (Levot, 2009c).

Handpiece (wand). For protection against body strike three passes of the traditional sickle-shaped wand are required, the first is along the backline from poll to tail. Further blows are made on either side, but overlapping the first blow. The multiple nozzles must be held in the fleece and combed through it to ensure penetration at skin level (Levot, 2009c). In longer woolled sheep the wand may be 'pumped' up and down in the fleece to ensure fluid pools in the fleece along the backline (Levot, 2009c). For wool longer than 5 cm, the Dutjet®, which has a metal shroud covering a T-shaped delivery tube, is recommended. The tube has three big-bore jets and the shroud has an angled back edge which opens the staple as the wand is drawn along the back of the sheep. This places the jets directly over the opening in the wool so that fluid is directed on to the skin (Levot, 2009c). A single blow from poll to tail is all that is usually required, drawn along at a rate such that fluid pools at the trailing edge of the shroud; any faster than this and a thorough treatment is not achieved, and any slower results in wasted jetting fluid (Levot, 2009c). More than one handpiece can be used at a time, provided the pump can provide the correct pressure at each handpiece. There should be sufficient length(s) of hose(s) attached to the jetting wand(s) to comfortably reach from one end of the race to the other.

VOLUME OF WASH APPLIED. Volumes of wash applied can vary between 1.125 and 4.5 l (2.0 pints–1.0 gal) per sheep, depending

on the area treated and the length of wool. In general, for body strike protection, a minimum of 0.5 l/month of wool growth is required. This can be calculated by timing how long it takes to jet this volume into a graduated container, which gives the minimum time that should be spent treating the backline of each sheep. The addition of a scourable food dye (e.g. Permicol Blue) or the use of an indelible pencil can be used to check wetting. Fluid will run around the body and drip from the belly of thoroughly treated sheep. Proper jetting for body strike protection should provide coverage on the belly, but rams and wethers may require direct treatment of the pizzle area (Levot, 2009c). Similarly, the poll of horned rams may need to be treated. If protection in the crutch is required, extra blows up the inside of each leg from the hock up to and over the tail are necessary (Levot, 2009c). However, this should not be a substitute for proper worm control and crutching (Levot, 2009c).

OPERATOR COMFORT. Hand jetting is relatively slow – Sinclair (1965) recorded 150 sheep/h per operator, and is also wasteful as the run off is not recycled. Jetting is best carried out in a concrete-floored race with adequate drainage to prevent puddles or mud forming. Trees or a roof will provide shade and a more comfortable working environment (Levot, 2009c).

MIXING THE JETTING WASH. When the jetting wash has been mixed, the pump should be started and the handpiece(s) held below the surface of the fluid in the sump in the 'on' position for about 5 min. This will provide thorough mixing and ensure that the hoses are full of jetting fluid (Levot, 2009c).

Spray-on application

Spray-on formulations are easier and more convenient to use than hand jetting. Spray-ons are generally applied undiluted along the backline, but in some situations additional bands are sprayed around the breech area. The advantage of spray-on formulations is their ease of application, as no additional water is required. This is a particular advantage for drier areas where water is scarce.

Many spray-ons are applied using power-assisted (compressed air or LPG gas cylinder) applicators that give constant delivery of the selected dose, ensure rapid and reliable refilling of the gun and reduce operator fatigue (Levot, 2009d). For smaller flocks, simple manual-squeeze type applicators are available and offer a cheaper and easily portable means of application (Levot, 2009d). It is essential that only applicators approved for a particular product are used and that they are calibrated before use (Levot, 2009d). It is also essential to follow the label instructions on dose rate and target area on the sheep. Fan nozzles can deliver at least 15 cm wide spray bands with each pass, provided that they are held 25 cm above the wool during application. The aim is to achieve total coverage of the areas needing protection. If two or more bands are applied there should be some overlap (Levot, 2009d).

Dose rates can be based on body weight or wool length. If the sheep to be treated vary in body weight it is useful to separate them into several weight classes or set the dose rate to the weight of the heaviest sheep in the mob. Sheep can also be drafted into groups of similar wool length. In groups of mixed shearings, or where young unshorn sheep vary by more than 2 months in age, it is prudent to treat according to the longest wool length (Levot, 2009d).

Spray-ons must be applied over the full body length (poll to tail) and equally along each side of the spine, as specified on the label. Failure to achieve this may lead to poor or incomplete movement of the product around the body and fleece of the sheep which, in turn, leads to reduced or incomplete protection and/or control (Levot, 2009d). Spray-on formulations are not suitable for treating struck sheep or sheep with soiled crutches; these should be drafted off for individual treatment or dagging before spray-on treatment (Levot, 2009d).

Non-saturation methods

Pour-ons and spot-ons

Spot-on and pour-on formulations (also known as backline treatments) are simple,

low-intensive labour and relatively stress-free methods for administering ectoparasiticide to sheep and goats. Pour-ons and spot-ons are purchased ready to use and deliver a measured, relatively high concentration of ectoparasiticide deposited in a band along the dorsal mid-line (backline) of the sheep. Innovative pour-on formulations have revolutionized chewing louse *(B. bovis)* control on sheep, particularly in Australia, with formulations containing the SPs deltamethrin (Bayvel *et al.*, 1981; Kettle *et al.*, 1983) and cypermethrin (Henderson and McPhee, 1983; MacQuillan *et al.*, 1983) widely used. Within a few years, pour-ons had gained 70% of the market share owing to their simplicity and low labour costs, with sheep treated immediately off-shear and returned to pasture.

FORMULATIONS. Pour-ons applied to animals for ectoparasite control can be classed as systemic or non-systemic. Systemic pour-on formulations contain ectoparasiticides effective through ingestion by the ectoparasite. These include the MLs doramectin, ivermectin or moxidectin, which can act either directly or indirectly on arthropods (ectoparasites) that feed on the skin, skin lipid or blood of the host: (i) by reaching the superficial skin lipid emulsion; (ii) through sebaceous and sweat gland secretions of the treated animal after a delay of about a week; (iii) through shed epidermal cells a month after application; or (iv) through circulating ectoparasiticide in the blood. Pour-on formulations containing the systemic MLs are effective against cattle ectoparasites but are not effective against sheep ectoparasites.

All pour-on formulations administered to sheep or goats are non-systemic (or 'translocatory') and kill ectoparasites through direct contact with the ectoparasiticide. The active ingredients in these pour-ons include OPs, SPs, IGRs or spinosyns.

The advantages of pour-ons and spot-ons include:

- There is no need to remuster sheep after shearing.
- There is less stress on sheep and a reduced risk of leaving any sheep untreated.
- The labour costs of application are low.
- Treated sheep are easily recognized by dye markings.
- There is no dip waste to contaminate the environment.
- It is easy to treat small numbers of sheep, including stragglers that are shorn later.
- It is easy to apply the correct dose to all sheep.
- There is a low risk of diseases associated with wet dipping.
- There is no operator exposure to chemical splash from dipwash.

The disadvantages of pour-ons and spot-ons include:

- They must be applied within 24h of shearing for the control of chewing lice.
- The product takes time to spread so lice are not killed immediately.
- There is very poor distribution of chemical around the sheep. Most of the product applied stays on the backline, reducing effectiveness in areas distant from the site of application.
- The uneven concentration of chemical on the sheep increases the likelihood of resistance.
- They may be ineffective on sheep that are not shorn.
- There will be high concentrations of chemical in long-wool sheep, resulting in high residue levels.

POUR-ON EQUIPMENT. Pour-ons/spot-ons require specially designed applicators/guns for their administration. Accurate application is essential; the correct length of the stripe and height of application are vital in the control of lice and blowflies.

APPLICATION. Formulations of pour-on differ, some are water based and some are oil based. It is important, therefore, that they are applied using the applicator gun specified for the product. Formulation excipients can cause irreversible damage to the seals and O-rings of inappropriate applicator guns, seriously affecting their efficacy.

It is also important that the correct nozzle attachment is used for the product and ectoparasite concerned (Table 9.4). In Australia, for ease of application, pour-ons can be administered to larger flocks using powered applicators with a T-bar. However, this equipment requires additional checks. Blowfly eggs are laid in the top quarter of the fleece, so for blowfly prevention a fan spray nozzle is required. The pour-on gun must be held approximately 45 cm (18 in) from the sheep to produce a band at least 10 cm wide from the poll to the tail of all animals. Half the dose should be applied along the back (to prevent/cure body strike) and half applied as an arc around the crutch and tail (to prevent/cure breech strike). Blowfly prevention using some alpha-cypermethrin-based pour-ons requires a T-bar nozzle placed directly against the fleece (with a minimum of 1.0 cm fleece recommended for effective control).

The length and accuracy of the stripe, height of application, partial application and missed sheep can all affect the efficacy of pour-ons in controlling ectoparasites. Most pour-on products contain a coloured dye to mark where the pour-on has been applied and, consequently, indicate which sheep have been treated.

OP backline treatments require dilution in water before use. The volume of OP pour-on applied to each sheep is much greater than for other pour-on treatments so the correct applicator must be used. The high volume (over 100 ml) applied may give better spread over the whole sheep. Some applicators use a timer rather than a direct volume measurement, and it is essential that the correct volume is delivered before commencing treatment.

DEPOSITION OF ECTOPARASITICIDE. Non-systemic ('translocatory') SP formulations are deposited in a band along the dorsal mid-line of the sheep, diffuse through the emulsion layer coating the wool fibres and absorb into the stratum corneum of the epidermis, accompanied by some dermal infiltration, mostly at the site of application (Pitman and Rostas, 1981; Jenkinson *et al.*, 1986). The ectoparasiticide then disperses around the body with the natural movement of skin grease and secretions.

In long-wool sheep the majority of ectoparasiticide remains close to the site of application and near the tip of the wool staple, decreasing with distance from the area of application on the dorsal mid-line (Kettle *et al.*, 1983). A concentration gradient results with the SP becoming less concentrated as it moves towards the belly. Despite the higher dose applied as a pour-on, concentrations in the upper flanks and lower flanks are generally lower than those achieved by plunge dipping. Uneven concentrations of deltamethrin have been recorded in fleece from different parts of the sheep within 24 h of application to offshears (Kettle *et al.*, 1983). There are also significant differences in ectoparasiticide concentration between the tip, middle and base portions of the wool staples from the back and lower flank.

Pour-ons take time to diffuse around the body. A 2.5% cypermethrin pour-on (at either 5 ml/10 kg body weight or 5 ml/20 kg body weight) applied from the crown of the

Table 9.4. Appropriate nozzle attachments for pour-on products (Source: NOAH, 2010).

	Blowflies				
Product	Prevention	Cure	Lice	Ticks	Headflies
Click	Fan spray	–	–	–	–
Vetrazin	Fan spray	–	–	–	–
Crovect	Fan spray	T-bar	Straight	Straight	T-bar
Dysect	T-bar	T-bar	T-bar	T-bar	T-bar
Spot-on	–	Dispenser Applicator	Dispenser Applicator	Dispenser Applicator	Dispenser Applicator

head to the rump has been shown to spread to the ventral areas (belly) within 1–2 h. Cypermethrin has been recorded moving at a rate exceeding 11.0 cm/h, but diffusion around the body generally takes time to attain lethal concentrations (Kettle *et al.*, 1983; Jenkinson *et al.*, 1986). The majority of dispersion is through the effect of gravity. In merino sheep some SPs (e.g. deltamethrin) can move from the backline to the flanks within 24 h, but peak concentrations may not be achieved until 4–11 days post-treatment and may not distributed on all parts of the fleece or along the staple. Dispersion may be slower in poor-quality fleece with high suint and low lipid concentrations. Plunge dipping offers a more uniform distribution of ectoparasiticide (Kettle *et al.*, 1983).

The natural flow of skin lipid from the head backwards and the effects of gravity may prevent an SP from diffusing backwards towards the muzzle and ears. In the UK, the majority of ticks (*Ixodes ricinus*) are found on the head/ears of sheep treated with an SP pour-on, with few found on the legs and inguinum until 41 days post-treatment (Mitchell *et al.*, 1986). However, other studies have demonstrated no significant difference in SP concentrations between the head and neck and the rest of the body (Kettle *et al.*, 1983; Jenkinson *et al.*, 1986).

FACTORS AFFECTING THE EFFICACY OF POUR-ONS. If the effective skin diffusion of a pour-on is impaired for any reason, then sublethal concentrations of ectoparasiticide will occur on some areas of skin. Some of the factors involved are discussed below.

Calculation of dose. The dose rates for all pour-on/spot-on formulations are calculated according to body weight. Consequently, it is essential to weigh pens of sheep/goats before administration and set the dose to the largest animal in the pen. Underdosing is a major cause of failure to eradicate lice and selects rapidly for resistance. A check needs to be run that the applicator is delivering the correct dose by squirting a few doses into a measuring cup.

Effects of rain. Some pour-on products cannot be applied if sheep are wet, and rain after treatment will affect their efficacy, so the release of recently treated sheep out into heavy rain should be avoided. Slower louse kills have been observed in wet fleeces, presumably because the nature of the yolk (grease and suint) emulsion has changed from a water-in-oil to an oil-in-water type.

Fleece factors. Application to sheep/goats with the correct length of fleece is essential as a long fleece can act as a barrier to effective dispersion. Slow or incomplete louse control is a feature on full-fleeced sheep treated with pour-on ectoparasiticides. A 2.5% cypermethrin pour-on was shown to gradually remove lice from most but not all full-fleeced sheep over a 7-week period (Heath and Bishop, 1988). This variation in efficacy has been attributed to the viscous nature of the fleece yolk, and to its increased volume in longer wool. In contrast, deltamethrin administered to off-shears will kill lice within 24 h and protect against reinfestation for at least 10 weeks although when applied to sheep with 3 weeks' wool growth it takes 2–7 days to kill lice, but protection lasts for 15 weeks (Kettle *et al.*, 1983). In Australia, it is recommended that louse control treatments are administered to off-shears, when louse populations are also at their lowest (Medley and Drummond, 1963; Chamberlain and Hopkins, 1971). Unshorn sheep must be kept separate from treated sheep until they can be shorn and treated.

Sheep/goat breed. German studies assessing the efficacy of flumethrin (1%), cypermethrin (1%), cyfluthrin (1%) and cyhalothrin (2%) backline treatments against *B. ovis* demonstrated variations in efficacy with respect to louse numbers and sheep breed (Liebisch and Beder, 1988). Light-to-moderate infestations were cleared after 7 days, but in heavy initial infestations and on merino sheep newly emerged lice were found after 21 days; no lice were found in the heavy initial infestations after 42 days, but the merino sheep required a second treatment (Liebisch and Beder, 1988).

Bates *et al.* (2001a) suggested that the pharmacokinetics of a 2.5% cypermethrin pour-on formulation may be different on goats with short hair as opposed to those with long fibre (e.g. angora goats). Inefficacy

may therefore be a case of product failure, and not ectoparasiticide resistance – as was previously recorded.

Inflammation and scar tissue. Alkaline conditions resulting from the secretions of inflamed skin can inactivate SPs, leading to a reduced louse kill. As SPs move through the stratum corneum and lipid intracellular spaces between the dermal cells (Jenkinson *et al.* 1986), inflammation and scar tissue at that level can act as a barrier beyond which the SP has difficulty migrating.

PLUNGE DIPPING VERSUS POUR-ONS. Kettle *et al.* (1983) showed that plunge dipping offered a more uniform distribution of SP than pour-on formulations. Despite the higher dose applied as a pour-on, concentrations in the upper flanks and lower flanks were lower than those achieved by plunge dipping.

Injections

The main advantage of injections over plunge dipping is that they are quicker and safer to use, cause less stress to the sheep (including pregnant ewes), and do not require any special handling facilities and fixed equipment (e.g. dip baths). Correct doses (according to body weight) will kill susceptible ectoparasites anywhere on the body as they feed, independently of fleece factors such as length, moisture and follicle density. There are also not the same environmental concerns over the disposal of spent products (Bates, 1993). The lack of special handling facilities and environmental concerns make this method an attractive alternative to plunge or shower dipping, with the added advantage of providing helminth control in late-season lambs and breeding ewes (Williams and Parker, 1996).

FORMULATIONS. Systemic MLs have both acaricidal and anthelmintic properties. At present the MLs doramectin, ivermectin and moxidectin are authorized for ectoparasite control in sheep and goats.

FREQUENCY OF TREATMENT. In the UK, doramectin is administered to sheep as a single intramuscular injection at a rate of 300μg/kg (Bates *et al.*, 1995b). Intramuscular injections of doramectin at 200μg/kg are only 93.3% effective in eradicating the sheep scab mite *P. ovis*, but at 300 or 400μg/kg doramectin is 100% effective (Bates *et al.*, 1995b). Noticeable failures were recorded in France, where it was administered subcutaneously at a rate of 200μg/kg.

Single (200μg/kg) subcutaneous injections of ivermectin failed to eradicate artificial infestations of the medium virulent isolate of *P. ovis*; they reduced mite numbers by 52% within 24h, 90% within 10 days and 96% within 20 days, but live mites were still detectable 86 days after treatment. The numbers of surviving mites correlated directly (r=0.96) with the mite burden at the time of treatment (Bates and Groves, 1991). The life cycle of *P. ovis* consists of egg, larva, protonymph, tritonymph and adult. Moulting occurs between each instar (see Chapter 2), and lasts for 12–36h. Moulting (pharate) mites cannot feed, and consequently may only ingest sublethal concentrations of acaricide once they are active. The potential for this evasive strategy is therefore increased the greater the mite population is at the time of treatment. Sheep scab mites can vary in virulence (Bates, 1999c, 2000a). Highly virulent isolates are characterized by rapidly progressing lesions with associated high numbers of mites. Isolates of low virulence are characterized by slow-growing lesions with associated low numbers of mites. Differences in the efficacy of single injections of ivermectin with respect to mite virulence are thus observed. Low-virulence populations (characterized by low mite numbers) can almost be eradicated after a single injection, yet significant numbers of mites survive within high-virulence populations (characterized by high mite populations). Double injections, however, eradicate all populations of sheep scab mites (Bates, 1994). Other researchers have observed that sheep severely infested with *P. ovis* required three subcutaneous injections of ivermectin for a complete cure (Sangwan *et al.*, 1995; Sargison *et al.*, 1995c).

Two sub-cutaneous injections of moxidectin at a dose rate of 200μg/kg bodyweight,

10 days apart, are 100% effective in the treatment of scab, and a single injection at the same dose rate will protect against infestation or re-infestation for up to 28 days (Parker *et al.*, 1999). O'Brien *et al.* (1996) demonstrated that moxidectin (200μg/kg) provided protection against natural and experimental sheep scab infection for up to 35 days.

LESION RESOLUTION. Clinical signs of sheep scab begin to resolve within days of plunge dipping, but the washing process and drying of the microclimate seen in plunge-dipped sheep is not generally observed after the use of an injectable endectocide (Bates and Groves, 1991). Consequently, scab lesions may take longer to resolve after injection, even after a second injection, and in many cases the lesion can continue to progress despite mite mortality (Bates and Groves, 1991). Animals can still present with severe episodes of irritation and hypersensitivity as long as the lesion or part of the lesion is still in contact with the skin (even though the mites themselves have been killed). Irritation should decrease as the fleece grows, lifting the scab away from the skin. Prolonged periods of irritation are seen in sheep with simultaneous infestations of both scab and chewing lice (*B. ovis*) at the time of treatment. No ML injection is effective against chewing lice, so once the scab mites have been killed, the louse populations grow rapidly as they feed on the scab lesion, thus continuing the irritation.

LONG-ACTING FORMULATIONS OF ML. A single dose (300μg/kg) of long-acting ivermectin equivalent to 1ml/30kg live weight can eradicate *P. ovis* from naturally infested sheep (Gómez-Blanco *et al.*, 1998). Long-acting formulations of ivermectin are licensed in Argentina and South Africa (but not currently in the UK), and are also effective against keds (*Melophagus ovinus*). Ivermectin is still detectable 30–35 days after treatment, but withdrawal periods are less of a problem for wool growers.

Long-acting formulations of moxidectin have been shown to eradicate existing infestations of *P. ovis* and protect against reinfestation for up to 90 days (Bates and Parker, 2007; Bates *et al.*, 2007a).

Oral drenching

Oral drenching (via a specifically designed drenching gun) has been the mainstay for endoparasitic helminth (gut worm) control for many years. Some oral anthelmintic formulations (particularly closantel and the MLs) are also effective against ectoparasites, particularly the nasal botfly, *O. ovis*. However, in Australia, where the discomfort and production losses caused by *O. ovis* do not justify specific treatment, control is generally a side effect of anthelmintic treatment (Brightling, 1988). Oral drenching with ivermectin can produce a 48% drop in scab mite (*P. ovis*) numbers within 24h of treatment, but with little further decline and no relationship between the initial mite burden and the extent of control (Bates and Groves, 1991). The apparent inefficacy of oral ivermectin may have significant effects on the epidemiology of sheep scab by extending the subclinical phase or selecting for resistance to other endectocides administered by injection.

The salicylanilide closantel has been shown to be effective against sucking lice (*Linognathus* spp.) (Butler, 1986) and larvae of the nasal botfly (*O. ovis*) when administered as an oral drench.

Controlled-release capsules (CRCs)

CRCs are delivered orally via a specifically designed gun (similar to an oral drench gun), and are designed to rest in the rumen and deliver a standard, pulsed, dose of ectoparasiticide over a long period of time. Ivermectin CRCs have been shown to be effective against sheep scab (*P. ovis*) (Bridi *et al.*, 1998; Rehbein *et al.*, 2000a,b) and have some efficacy against chorioptic scrotal mange (*Chorioptes bovis*) and *L. cuprina* breech strike.

Pyrethroid-impregnated ear tags

Polymer matrix ear tags containing 8.5% w/w cypermethrin have been shown to reduced chewing lice (*B. ovis*) numbers by

89% and 85%, 16 and 38 weeks after application, respectively (James *et al.*, 1989). Ear tags and head caps have also been shown to reduce cutaneous damage induced by *Hydrotaea irritans*.

Choice of Ectoparasiticide

A number of factors must be considered when choosing an ectoparasiticide and its method of application. The most important are accurate identification of the ectoparasite, the curative and protective efficacy of ectoparasiticide against the identified ectoparasite, ectoparasiticide resistance in the target parasite, effects of the chosen treatment on other ecto- or endo-parasites, occupational health and safety, and effects on the environment. Other relevant factors include the size of flock to be treated, the physiological condition of the sheep to be treated, marketing the end product, the availability of labour and facilities, and the expected weather before, during or after treatment.

Accurate identification of the ectoparasite

Chapter 7 (and some parts of earlier chapters) of this book describe effective methods for confirming an ectoparasite problem in a flock or herd and for identifying the causative organism. Accurate ectoparasite identification is essential. Administration of an inappropriate control strategy may require repeat treatment. The timespan between such treatments can prolong the suffering of the host (a significant welfare issue) and possibly affect the marketing of meat, wool or milk through the unacceptable condition of the infested sheep or goats and/or excessive meat or fleece withholding periods. There are also increased costs from the purchase of new ectoparasiticide and maybe extra feed requirements. Futhermore, there is the possibility of selection for resistance in unidentified non-target parasites, which may provide future problems.

Efficacy of the ectoparasiticide

Since the deregulation of sheep scab (caused by *P. ovis*) in the UK in 1992, there is now a wider choice of products for the control of ectoparasites. Stock owners are not obliged to dip and will seek alternatives to that practice, particularly those suffering from the toxic effects of OPs (Bates, 1993). This wider choice has also led to inappropriate use. A survey carried out by Meat Promotion Wales in the UK highlighted the inappropriate use of ectoparasiticides by some sheep farmers. For example, 9.0% of respondents used SP or IGR pour-ons for the control of sheep scab, and none of these pour-ons are effective against *P. ovis*. The survey also showed that 17.1% and 18.6% of respondents used ML injections or cyromazine and dicyclanil pour-ons for the control of lice (*B. ovis*) or ticks (*I. ricinus*), respectively. Again, neither ML injections or cyromazine or dicyclanil pour-ons are effective against *B. ovis* or *I. ricinus*. The chosen product *must* be effective against the ectoparasite or ectoparasites confirmed as present in a flock.

There are a number of products available for the control of sheep/goat ectoparasites. Some products are broad spectrum, and control all the major ectoparasites; others have a medium spectrum of activity; and yet others have a very narrow spectrum of activity, being specific against only one or two ectoparasites. Some of these products (i.e. those that contain OPs) are prohibited under organic regulations, but they should be retained as possible one-off treatments to eradicate ectoparasites from a flock should resistance to other ectoparasiticides be indicated – together with the associated welfare problems.

All treatments should be administered *strictly* according to national regulations and according to the manufacturer's instructions. Dip baths must be accurately calibrated, and where injections are considered the sheep should be accurately weighed. The entire flock and all contact sheep should be treated, not just those presenting with the clinical signs of infestation. Other sheep may have subclinical disease, and be recycling parasites within the flock.

Flock/herd owners are warned to read the label instructions that state the spectrum of efficacy of the product and indicate whether it is both curative and protective against reinfestation by permanent ectoparasites. The rubbing and scratching of heavily infested animals will deposit live scab mites (*P. ovis*) and chewing lice (*B. ovis*) into the environment. As noted previously, *P. ovis* can survive off the host for at least 17 days and *B. ovis* for a similar period (Morcombe *et al.*, 1994; O'Brien *et al.*, 1994a). Consequently, if animals are reintroduced to the original contaminated accommodation, they are likely to be reinfested. For sheep scab, the prolonged period for complete resolution of clinical disease seen after treatment with the MLs increases the chances of sheep rubbing and thus contracting residual mites from the environment. Plunge-dip formulations containing diazinon and some formulations of high-cis cypermethrin can protect against reinfestation by *P. ovis* for 21–28 days on sheep with 1.0 cm of fleece, and longer on sheep in full fleece. Moxidectin is the only injectable ML offering protection against reinfestation by scab mites for 28 days (O'Brien *et al.*, 1996). Long-acting formulations of moxidectin can protect against reinfestation by *P. ovis* for 90 days (Bates *et al.*, 2007a).

If a product does not claim protection, treated animals should not be returned to infested pasture/buildings following treatment. Clean facilities must be made available – although this may not always be possible.

Mange

*Sheep scab (*Psoroptes ovis*)*

Until the development of ML injections, plunge dipping in OC, OP, SP or formamidine (amitraz) dipwash was the only effective method of controlling sheep scab mites (*P. ovis*).

OP-based plunge-dipping formulations containing diazinon (Kirkwood and Quick, 1981; Ahmad *et al.*, 1993), phoxim (sebacil) (Liebisch *et al.*, 1978) or propetamphos (Kirkwood and Quick, 1982; Bramley and Henderson, 1984) and plunge-dipping formulations containing the SPs flumethrin (Kirkwood and Bates, 1987a,b), fenvalerate or high-cis cypermethrin (O'Brien *et al.*, 1997) have all been shown to be effective in both curing and protecting against sheep scab. In all cases, the instructions accompanying the plunge-dip formulation will detail the make-up and replenishment concentrations for the product. Sheep must be dipped for 1 min with the head immersed at least twice. Under laboratory and field conditions, propetamphos at a dipwash concentration of 125 mg/l eradicated sheep scab and protected against reinfestation for over 4 weeks (Bramley and Henderson, 1984). Phoxim (sebacil) at a concentration at 0.01% has been shown to be 100% effective against *P. ovis* after 24 h (Stendel, 1980).

The amidine amitraz has been shown to be effective against *Psoroptes*, *Sarcoptes* and *Chorioptes*. Clinical trials carried out in Argentina, France, Inner Mongolia and Syria have demonstrated that a 12.5% formulation (at an initial concentration of 0.05%) was 100% effective in curing sheep scab (*P. ovis*), but only after two dippings 10 days apart (Muñoz-Cobénas *et al.*, 1978; Curtis, 1985). Although effective, amidines are very expensive and are only used as 'OP resistance breakers'; the dipwash has to be stabilized in the dip bath using calcium hydroxide.

Scab mites (*P. ovis*) are relatively immobile on the host, and move only as the lesion progresses. It is essential, therefore, that effective concentrations of ectoparasiticide are deposited over the entire body, particularly at skin level. In the UK, in the 20-year period between scab eradication (1953) and its reintroduction (1973), shower dipping became more popular than plunge dipping. On the reintroduction of scab, it was clear that shower dipping had failed to eradicate *P. ovis*, mainly as a result of insufficient acaricide reaching the cryptic sites (particularly the ears, external auditory canal (EAC), infra-orbital fossae (IOF), inguinal fossae, perineum and crutch) or the ventral body surfaces of the sheep (Kirkwood *et al.*, 1978). Shower dipping shorn or unshorn

and extensively infested sheep with 0.005% lindane dipwash (for 2.0 min via ten 9.0 mm floor nozzles, followed by 4.0 min from the upper nozzles) failed to eradicate *P. ovis* in the crutch (Kirkwood *et al.*, 1978). Recent studies have demonstrated that diazinon dipwash at an initial concentration of 100 mg/l administered via a (monsoon type) shower dip, with 3.0 min showering from the top boom and 1.0 min from the bottom jets, was 100% effective in eradicating an OP/SP-susceptible isolate of *P. ovis* from artificially infested sheep with 1.0 cm of fleece. Dipwash made up with the SP high-cis cypermethrin administered in a similar manner was only 90% effective in eradicating the same OP/SP-susceptible isolate of *P. ovis* (Bates *et al.*, 2005). SP pour-ons are not effective against scab mites (*P. ovis*) and their routine use in the UK for the control of other ectoparasites may have selected for resistance to SP dips or augmented existing SP tolerance within scab mite populations (Bates, 1998).

The lack of special handling facilities and environmental concerns make injections of MLs an attractive alternative to plunge dipping, with the added advantage of providing helminth control in late-season lambs and breeding ewes (Williams and Parker, 1996). MLs currently licensed for the control of sheep scab (*P. ovis*) include doramectin, ivermectin and moxidectin, administered either by injection (subcutaneous or intramuscular) or by constant release capsule (CRC).

- Doramectin is administered as a single intramuscular injection at 300 µg/kg body weight (Bates *et al.*, 1995b).
- Ivermectin is administered as two subcutaneous injections at 200 µg/kg body weight, 7 days apart (Soll *et al.*, 1992).
- Moxidectin is administered as two subcutaneous injections at 200 µg/kg body weight, 10 days apart (Parker *et al.*, 1999).

Single injections of the ML ivermectin (at 200 µg/kg body weight) have been recorded as effective against *P. ovis* (Doganay, 1988). However, Bates and Groves (1991) demonstrated that a single subcutaneous injection of ivermectin at 200 µg/kg body weight failed to eradicate *P. ovis* from artificially infested sheep. Repeat injections, after 7 days for ivermectin and 10 days for moxidectin, are necessary to kill larval *P. ovis* emerging from eggs or moulting larvae or nymphs. Double injections are more effective (Bates, 1994), but three consecutive weekly injections of ivermectin (200 µg/kg body weight) may be required to eradicate *P. ovis* from severely affected sheep (Sargison *et al.*, 1995c). Sangwan *et al.* (1994) recorded that three subcutaneous injections of ivermectin at the higher dose of 400 µg/kg body weight were required to completely cure *P. ovis* infestations.

The efficacy of a single injection of ivermectin appears to decrease the higher the initial mite burden (Bates and Groves, 1991). The higher the mite population, the higher the sub-population of eggs and post-embryonic instars in the moulting (pharate) state. High mite populations can be found in severely infested sheep and in infestations of highly virulent mite isolates. Laboratory trials have shown that single subcutaneous injections of ivermectin (at 200 µg/kg bodyweight) can eradicate slow, chronic strains of *P. ovis* or at least reduce the mite burden by over 99% whereas mite burdens of acute virulent strains may only be reduced by 77% (Bates, 1994).

Doramectin is administered as a single, intra muscular injection at 300 µg/kg bodyweight. Single injections at 200 µg/kg were only 93.3% effective in controlling *P. ovis* (Bates *et al.*, 1995b).

As previously noted, the washing process and drying of the microclimate seen in dipped sheep is not generally observed after the use of an injectable ML, and injected ivermectin has no effect on the resolution of the sheep scab lesion, which can continue to progress despite mite mortality (Bates and Groves, 1991). This also applies to injections of doramectin or moxidectin. Animals can still exhibit severe bouts of irritation and hypersensitivity as long as the lesion or part of the lesion is still in contact with the skin (even though the mites themselves have been killed), although irritation decreases as the fleece grows and lifts the scab away from the skin.

ML injections offer varying periods of protection against (re)infestation. Rubbing and scratching of heavily infested sheep will deposit live scab mites into the environment (e.g. on to fencing, bushes, lorries, shearing combs, etc.) so, as scab mites can survive off the host for at least 17 days (O'Brien *et al.*, 1994a), if sheep are reintroduced to the original contaminated accommodation, they are likely to be reinfested. The prolonged period for complete resolution of clinical disease increases the chances of sheep rubbing and thus contracting residual mites from the environment. If an ML does not claim protection against scab mites (*P. ovis*), sheep should be moved, directly after injection, to clean accommodation/grazing that has not held infested sheep for at least 3 weeks. Single subcutaneous injections of moxidectin at (200µg/kg body weight) will protect against infestation or reinfestation by *P. ovis* for 28–35 days after treatment (O'Brien *et al.*, 1996; Parker *et al.*, 1999). Injections of ivermectin or doramectin offer little protection against *P. ovis*.

Long-acting (LA) formulations of MLs are available. These allow MLs that previously required two injections to remain residual in the sheep/goat long enough to kill both hatching eggs and mites coming out of moulting. These LA formulations also offer considerably extended periods of protection compared with the double-injection formulations. A significant drawback of LA formulations of MLs is their very long meat withholding periods. LA formulations of ivermectin (at a dose rate of 300µg/kg body weight) are available for sheep scab control, and are administered as a single subcutaneous injection (Gómez-Blanco *et al.*, 1998). Single subcutaneous injections of a 2% LA formulation of moxidectin are also available that claim complete eradication of *P. ovis* on naturally infesting sheep (Bates and Parker, 2007) and offer protection against infestation for at least 90 days (Bates *et al.*, 2007a).

Intra-ruminal CRCs that deliver ivermectin at a rate of approximately 20–40µg/kg daily for 100 days (for 20–90kg sheep body weight) have been shown to be completely effective in eliminating *P. ovis* mites within 28 days of administration. The ivermectin CRC also protected against the establishment of *P. ovis* when challenged 21 and 28 days after administration (Bridi *et al.*, 1998; Forbes *et al.*, 1999; O'Brien *et al.*, 1999).

Oral drenching with ivermectin can produce a 48% drop in scab mite (*P. ovis*) numbers within 24h of treatment, but with little further decline and no relationship between the initial mite burden and the extent of control (Bates and Groves, 1991). The apparent inefficacy of oral ivermectin may have significant effects on the epidemiology of sheep scab by extending the subclinical phase or selecting for resistance to other endectocides administered by injection.

*Psoroptic ear mites (*Psoroptes cuniculi*)*

Psoroptes mites are known to colonize deep within the EAC of sheep and goats. Plunge dipping sheep in wash containing a blue dye did not penetrate the ear canal completely (Bates, unpublished data). Mites in the ears could therefore survive plunge dipping and their exposure to sublethal concentrations of acaricide could select for resistance. It is also unlikely that shower dipping, jetting or pour-ons will deliver an effective dose of ectoparasiticide deep within the ear canal. Systemic injections of one of the MLs are more effective.

Single subcutaneous injections of the ML ivermectin (200µg/kg body weight) have been shown to be effective against *P. cuniculi* colonizing the EAC (Odiawo and Ogaa, 1987; Bates, unpublished data).

*Chorioptic mange (*Chorioptes bovis*)*

Plunge dipping sheep infested with *C. bovis* in dipwash containing the OPs phoxim or diazinon has shown efficacy, but only after repeat treatments. Phoxim (0.05%) is effective after two dippings 10 days apart (Kusiluka and Kambarage, 1996), and diazinon (0.15%) after three treatments (Ahmad *et al.*, 1993; Maqbool *et al.*, 1994).

Single topical applications of the amidine amitraz (0.05%) or the synthetic pyrethroid fenvalerate (0.05%) have been successful in eradicating *C. bovis* from goats (Wright *et al.*, 1988).

Single subcutaneous injections of ivermectin at 200 mg/kg body weight or double injections 14 days apart can suppress, but not eradicate, *C. bovis* on sheep (Yeruham *et al.*, 1991). No conclusion could be drawn on the efficacy of intramuscular injections of doramectin (300 µg/kg body weight). The use of MLs such as doramectin or ivermectin for the elimination of *C. bovis* may be limited by the feeding behaviour of the mites (Sargison *et al.*, 2000).

Ivermectin CRCs have been shown to be effective against chorioptic scrotal mange caused by *C. bovis*.

*Sarcoptic mange (*Sarcoptes scabiei var. ovis*)*

Sarcoptic mange in sheep can be difficult to control. Christodoulopoulos (2006) remarked that plunge dipping, pour-ons and showers were ineffective against sarcoptic mange on sheep owing to the location of the lesions on the hairy parts of body, with little persistence of the ectoparasiticide in the hair. However, Kusiluka and Kambarage (1996) reported that single plunge dippings in the OPs diazinon (0.05%), phoxim (0.1%) or coumaphos (0.05%) could be effective. Other authors recommended repeat treatments. In Iran, clinical studies have shown that plunge dipping in diazinon (0.15%) cured 40% of sarcoptic mange cases after one application and 100% of cases after two applications (Maqbool *et al.*, 1994). Phoxim (0.2%) may also require a repeat treatment after 10 days (Umer and Irmak, 1993). Diazinon administered as a 0.15% spray was shown to be 100% effective against *S. scabiei* var. *ovis* after two treatments (Ahmad *et al.*, 1993). Washing sheep using a 0.1% fenvalerate emulsion three times at 7-day intervals, showed some efficacy against sarcoptic mange. Administration of a 1.0% flumethrin pour-on (2 ml/kg body weight) has also been shown to be effective.

Two subcutaneous injections of ivermectin (at 200 µg/kg body weight) have been shown to be 100.0% effective in controlling *S. scabiei* var. *ovis* in sheep (Wasfi and Hashim, 1986). Live mites can be present up to 8 days post-treatment, but treated animals are mite free thereafter (Sekar *et al.*, 1997). However, the severity of infestation may affect the efficacy. Ivermectin administered as a single subcutaneous injection (at 200 µm/kg body weight) was shown to be effective in controlling mild *S. scabiei* var. *ovis* infestations in sheep (Zeybek, 1985; Shastri *et al.*, 1990; Pangui *et al.*, 1991). Moderate infestations require two injections, 10, 14, 15 or 21 days apart, for a complete cure, but severely infested sheep were not cured by double injections (Shastri *et al.*, 1990; Umer and Irmak, 1993; Özer *et al.*, 1998). Christodoulopoulos (2006) reported that three subcutaneous injections, 7 days apart, are required to eliminate sarcoptic mange mites. Ivermectin administered to goats as two subcutaneous injections (at 200 µm/kg body weight) 7 days apart was shown to be more effective than plunge dipping three times in diazinon (1/1000) at weekly intervals (Al-Badrani and Al-Khafaji, 2000).

Two or three subcutaneous injections of moxidectin (200 µm/kg body weight) 7 or 12 days apart, respectively, are required to remove all living *S. scabiei* var. *ovis* (Corba *et al.*, 1995; Hidalgo-Arguello *et al.*, 2001). Two subcutaneous injections of doramectin (300 µm/kg body weight) 12 days apart are also effective (Christodoulopoulos, 2006).

*Psorobic mange (*Psorobia ovis*)*

Plunge-dipping wash made up with the OP phoxim (sebacil) has been shown to be effective against *Psorobia ovis* (Stendel, 1980).

Single subcutaneous injections of ivermectin (200 µg/kg body weight) have been shown to be highly effective against *P. ovis* in South Africa (Soll and Carmichael, 1988). Ivermectin and rotenone, when administered in the spring, have been shown to be effective against reproductively active *P. ovis* in sheep whose defences were improved by a high plane of nutrition, although eradication was unlikely (Johnson *et al.*, 1989a). However, the use of ivermectin or other MLs specifically for the control of psorobic mange is not recommended owing to possible selection for anthelmintic resistance in gut worms.

Demodectic mange (Demodex spp.)

Plunge dipping three times in a dipwash containing trichorfon or phoxim at 6–7 day intervals has been shown to be effective against demodectic mange; shorn sheep are dipped for 30 s and full-fleeced sheep and goats are dipped for 60 s. The optimum time for treatment is 6–8 weeks after shearing (Baumgartner and Prosl, 1987).

Ticks

Plunge dipping in diazinon at an initial concentration of 400 mg/l is effective in protecting sheep against *I. ricinus*. Large-scale field trials using the amidine amitraz for the control of *I. ricinus* on 15 farms in Scotland and northern England demonstrated that plunge dipping in amitraz or the OP chlorpyrifos afforded satisfactory control for at least 6 weeks, with reduced activity for up to 8 weeks (Platt, 1978).

Pour-on formulations containing SPs are effective against ticks (Mitchell *et al.*, 1986), but have varying efficacy between tick species. In the UK, SP pour-ons are widely used for the control of *I. ricinus* and help in preventing tick-borne diseases. The use of SP pour-ons has been reported to reduce tick infestations and the incidence of tick-associated diseases in lambs, more than that achieved by dipping in OP acaricides (Hardeng *et al.*, 1992). However, the use of SP pour-ons for 3 consecutive years did not seem to affect the prevalence of tick-borne fever (TBF). In contrast, the incidence of lameness (tick pyaemia) or sudden death through *Pasteurella haemolytica*-associated septicaemia, often in association with TBF, was reduced (Hardeng *et al.*, 1992).

Pour-ons may not be effective against all species of tick associated with sheep and goats. There are differences in the preferential sites of attachment between tick species, implying that the application of pour-ons may not reach these sites in effective concentrations (Fourie and van Zyl, 1991; Fourie and Kok, 1995). Hamel (1987) treated karakul sheep against *Hyalloma truncatum* on the back, belly and tail, and in the axillae and groin, and suggested that the site of application may influence the efficacy of a pour-on formulation.

Spot-on treatments of the anogenital region of sheep are often carried out by South African farmers. Ticks infesting this area are conspicuous and therefore easy to treat; furthermore, failure to treat may result in blowfly strike at the tick feeding site (Leipoldt, 1996). Thus, optimal control efficacy can be achieved by administering pour-on/spot-on formulations directly to the body regions where defined tick species preferentially attach (Fourie *et al.*, 2001). Application of a flumethrin-based pour-on directly to the anogenital region of sheep provided excellent and prolonged protection against ticks at this site, especially in merino sheep, but provided little protection to ticks attaching elsewhere on the sheep (Fourie *et al.*, 2001).

Ixodes rubicundus preferentially attaches to the ventral surfaces of sheep. Hence, application of a pour-on formulation to the dorsal mid-line to control this tick is not optimally effective (Fourie *et al.*, 2001). The control is best achieved through the administration of a pour-on to the axillae and groin areas (Kok *et al.*, 1996). For adult ticks attaching preferentially to the dorsal body regions (head, withers and back), for example *I. ricinus* and *Dermacentor marginatus*, application of a pour-on to the dorsal mid-line can result in high levels of control (Howell *et al.*, 1978).

Systemic insecticides such as the MLs or closantel can affect the fecundity and fertility of ticks. The oral administration of closantel has been shown to have an effect on the one-host cattle tick, *Boophilus microplus*. At an oral dose rate of 22.5 mg/kg body weight, closantel did not affect the mortality or oviposition of adult *B. microplus* (or *Boophilus decoloratus*), but did reduce egg hatching by 60–100%, resulting in a decreased final tick burden of above 99% (Lombardero and Luciani, 1982). Closantel can also have an effect on tick species that have three hosts.

Anecdotal evidence from sheep farmers in the UK indicated that closantel, administered as an anthelmintic drench to control

liver fluke (*Fasciola hepatica*), was also controlling *I. ricinus*. When administered to sheep (orally at a dose rate of 10 mg/kg body weight) closantel can have a marked effect on the fecundity and egg viability of *I. ricinus* (Bates *et al.*, 1995a). The effects were greatest when ticks were attached and feeding at the time of dosing. The most probable mode of action on *I. ricinus* is that plasma-bound closantel ingested by the tick while feeding affects its internal respiration by uncoupling phosphorylation. The dose used (10 mg/kg body weight) was insufficient to cause mortality but sufficient to have a direct effect on ovarian development, and resulted in a reduced number of eggs deposited and a reduction in egg viability (Bates *et al.*, 1995a).

Lice

*Sheep chewing louse (*Bovicola ovis*)*

Plunge dipping sheep in the OPs phoxim (sebacil) or propetamphos has been shown to be effective against *B. ovis* (Stendel, 1980; Bramley and Henderson, 1984). Plunge dipping in propetamphos at a dipwash concentration of 100–200 mg/l protected sheep against *B. ovis* for 16 weeks (Bramley and Henderson, 1984). Hand jetting long-wool sheep with ivermectin jetting fluid diluted in water at 0.03 mg/ml resulted in an immediate reduction in the numbers of *B. ovis* and no lice were observed after day 14 post-treatment (Rugg *et al.*, 1995).

The decision as to how to treat a flock infested with chewing lice depends on the course of the infestation. If the infestation is ongoing, then it is necessary to reassess management practices, particularly mustering, as well as equipment and chemical use. If the usual treatment strategy is no longer working there is little point continuing with it. There may be wider problems, e.g. sheep missing treatment or receiving ineffective treatment, contact with stray sheep, or ectoparasiticide resistance. These issues need to be confronted before a new treatment strategy is selected. In Australia, a computerized decision support system called 'LiceBoss' (www.liceboss.com.au) has been developed that helps producers to choose the best course of action.

TIMING OF TREATMENTS. Treatment immediately after lice are diagnosed may not always be the best approach. Fleece length can have a significant effect on the efficacy of topically applied formulations. The efficacy of formulations with a claim to cure or protect against *B. ovis* depends on wool length, which is classified as off-shear (directly after shearing), short-wool (under 6 weeks off-shears, fleece length between 1.0 and 1.5 cm) or long-wool (over 6 weeks off-shears, fleece length above 1.5 cm).

In Australia, it is recommended that louse control treatments be administered to off-shears, when louse populations are at their lowest (Wilkinson, 1985). In Argentina, treatment is also directly after shearing in the late spring/early summer and is largely dependent on the movement of the shearing gangs from the north to the south of the country (Bulman, personal communication). Weather is an important factor in the timing of shearing and louse control; when the snow is late, farmers are reluctant to shear until the weather has improved.

Delaying treatment until shearing time has to be weighed against the projected losses in wool production up to treatment. This depends on the time between diagnosis and shearing, and the level of infestation. The welfare of the infested sheep should also be considered, given the possible negative consequences of treating sheep in long wool. Long-wool treatments can be effective, enabling wool producers to treat infested sheep without shearing, and thus prevent wool damage until the next shearing.

A fleece is a large, oily, waterproof coat. Treatment of short wool minimizes the 'dilution' effect, increasing the chemical concentration at the skin surface (where lice feed). Application is easier, and lice are under their most environmental stress on recently shorn sheep. The procedure is also less costly and stressful on stock, and there is less residual ectoparasiticide at the next shearing. A greater proportion of lice come

into contact with the ectoparasiticide and this reduces the volume of dip chemical that is necessary. In addition to the advantages of short wool already mentioned, sheep markedly increase grease production within 24 h of shearing, and the active ingredient of the treatment binds more readily with this grease, on which lice actively feed.

OFF-SHEARS. Approximately 80% of all treatments applied for louse control in Australia are pour-ons (backline treatments). OP pour-ons are applied within 24 h of shearing. Pour-on products containing the OP diazinon are not available in the UK, but were reintroduced to the Australian market in 2005 to help counter resistance problems with SP pour-ons. OP pour-ons require dilution in water before use. The volume applied to each sheep is much greater than for other (SP or IGR) pour-on treatments, so the correct applicator must be used. Diazinon-based pour-on rapidly removed *B. ovis* from moderately infested newly shorn sheep, with some sheep protected from reinfestation for 8–10 weeks (Heath and Bishop, 1988). In the UK, an experimental propetamphos-based pour-on gave more than 99% control of *B. ovis* and protected against reinfestation for 4 months (Ormerod and Henderson, 1986).

Pour-on formulations containing SPs are effective against chewing lice (*B. ovis*) (Henderson and McPhee, 1983; Rundle and Forsyth, 1984). Pour-ons containing alpha-cypermethrin (NOAH, 2010), cypermethrin (Henderson and MacPhee, 1983), cypermethrin + PBO or deltamethrin (Bayvel *et al.*, 1981; Kettle *et al.*, 1983),) are now widely used for chewing louse (*B. ovis*) control. In Australia and New Zealand, SP pour-ons are applied within 24 h of shearing. In the UK, they are applied to long-wool sheep (NOAH, 2010). There is currently widespread resistance to SPs, and they should not be used in flocks where there have been previous treatment failures.

Deltamethrin formulations applied to off-shears kill *B. ovis* within 24 h and protect against reinfestation for at least 10 weeks, but when applied to sheep 3 weeks after shearing, all lice are killed within 2–7 days and protection lasts for 15 weeks (Kettle *et al.*, 1983). This difference has been attributed to the viscous nature of the fleece yolk and its increased volume with the longer wool staple (Sinclair, 1977) and the poor fleece quality, i.e. its high suint concentration (Kettle *et al.*, 1983).

IGR pour-ons, containing diflubenzuron or triflumuron, can be applied within 24 h of shearing, or up to 7 days after shearing. These have been widely used to good effect in Australia and New Zealand, but there is evidence that resistance to them is growing.

SHORT-WOOL SHEEP (UNDER 6 WEEKS OFF-SHEARS). Ectoparasiticides for chewing louse control can be applied by plunge dipping, shower dipping or hand jetting. The short wool (1.0–1.5 cm) allows for better penetration to skin level (and retention). In Australia, New Zealand and the UK, AJRs are principally used for the prevention of blowfly strike (Lund and Kelly, 1994; Bates, 1999d). AJRs do not wet all sheep to skin level and are not recommended for eradicating *B. ovis*. However, if they conform to minimum standards (see Table 9.5) and are used off-shears, control of lice may be achieved.

OP formulations are effective when applied to short-wool sheep via plunge dipping (coumaphos or diazinon), shower dipping (chlorpyrifos, coumaphos, diazinon or propetamphos) or hand jetting (diazinon, diazinon + rotenone + PBO, chlorpyrifos, propetamphos). OP formulations for application via plunge or shower dips were withdrawn from the Australian market in 2007 for health and safety reasons. Sheep can be plunge dipped in diazinon using a cage immersion dipping system with an APVMA (Australian Pesticides and Veterinary Medicines Authority) permit, but owing to the high cost of the equipment and safety requirements, this system is most likely to be used only by contractors. SP formulations applied via saturation methods pose a very high risk to the environment from surplus wash reaching watercourses. Effective SP formulations are applied to short-wool sheep by shower dipping (cypermethrin) only.

Table 9.5. Optimal design of automatic jetting races (AJRs) for effective penetration performance (Source: Lund and Kelly, 2003).

Number of top spray bars	Two
Number of nozzles per top bar	Five
Top bar orientation	Longitudinal, 100 mm apart
Top nozzle size	Solid stream (3/16 diameter)
Top nozzle direction	Straight down, angled in
Top bar height above sheep	150 mm maximum
Number of bottom bars	One
Number of nozzles per bottom bar	Three
Bottom nozzles size	Solid stream (3/16 diameter)
Bottom bar arrangement	Across
Bottom bar angle	30° forward
Sheep speed	Less than one/s
Manifold and valve size	40 mm diameter
Hoses and spray bars	25 mm diameter
Pressure cylinder volume	No larger than 2.5 l
Valve type	Quick-acting gate or butterfly valve
Operating pressure at nozzles	450 kPa
Pump specification	6 l/s at 550 kPa (8 hp, ≈5.9 kW)

IGRs are applied to short-wool sheep by shower dipping (diflubenzuron) or hand jetting (diflubenzuron or triflumuron). Diflubenzuron and triflumuron kill lice when they moult and therefore do not kill active adult lice, although they will prevent eggs hatching. Adult lice can live for approximately a month after their last moult, and consequently small numbers of lice can be seen 1–2 months after treatment. These survivors will be low in number and will not be enough to cause wool damage; they do not indicate resistance. IGRs break down slowly in the fleece and can remain at relatively high concentrations for several months after treatment. However, they will not protect sheep against infestation up to the next shearing, so the period of protection is not sufficient to reduce management practices to avoid new infestations in the flock.

The spinosyn spinosad is licensed in Australia and New Zealand for the control of *B. ovis* and is safe to use and effective if applied correctly by shower dipping or hand jetting to short-wool sheep. Spinosad kills lice on contact and has low toxicity to humans. It is safe to the environment owing to its rapid breakdown. The amidine amitraz is effective against *B. ovis* on short-wool sheep when applied by shower dipping. Other products registered in Australia for use via a shower dip include mixes of fluorosilicate, rotenone and sulfur. These are relatively safe for both humans and the environment, but they are sold as a powder, so there are problems with settling out quickly in the dipwash, making it difficult to ensure that all of the flock is thoroughly treated.

LONG-WOOL SHEEP (OVER 6 WEEKS OFF-SHEARS). There are a limited number of products available for treating long-wool (over 1.5 cm) sheep, because the wool length acts as a barrier to total saturation to skin level and repeat treatment may be required at the next shearing. The ability to saturate sheep to skin level is essential for effective louse control (Higgs *et al.*, 1994, Lund *et al.*, 1996). Effective long-wool treatments are generally applied by plunge dipping, hand jetting or by pour-on. Plunge dipping formulations can contain OP (diazinon) or SP (cypermethrin, flumethrin). Long-wool hand jetting formulations can contain OPs (diazinon, propetamphos), IGRs (diflubenzuron), MLs (ivermectin) or spinosyns (spinosad). Long-wool pour-on treatments can contain an SP (cypermethrin) or an IGR (diflubenzuron). These rarely eradicate *B. ovis* and are generally only used as an emergency stop-gap

measure to minimize wool damage before shearing but will cause high ectoparasiticide residues in the wool at shearing. Chewing lice (*B. ovis*) are relatively immobile in the fleece and generally remain on the upper body (Scott, 1952). This decreased mobility lessens the chance of contact with ectoparasiticide in the fleece. High concentrations in the upper fleece are therefore more effective.

Cypermethrin-based pour-on formulations with high *cis*:*trans* isomer ratios (80:20) (high-cis cypermethrin) can achieve a higher level of control of *B. ovis* (97–100% from 4 to 16 weeks after application) than ordinary cypermethrin formulations (85% control 4 weeks after application) (Heath *et al.*, 1992). High-cis cypermethrin may provide a better level of control in long-wool sheep than cypermethrin by compensating for the diluent effect of fleece lipid (Heath *et al.*, 1992).

In vitro bioassays have shown that ivermectin and abamectin are highly effective against *B. ovis*, with similar effects on pyrethroid-susceptible and pyrethroid-resistant strains, indicating that there was no cross resistance to ivermectin (Rugg and Thompson, 1993). Hand-jetting long-wool sheep with ivermectin jetting fluid diluted in water at 0.03 mg/ml resulted in an immediate reduction in the numbers of *B. ovis*, with no lice observed after day 14 post-treatment (Cramer *et al.*, 1983; Rugg *et al.*, 1995). This reduction in louse numbers was recorded up to 13 weeks post-treatment and was effective against SP-resistant strains of *B. ovis* (Cramer *et al.*, 1983).

MIXING TREATED AND UNTREATED SHEEP AND LAMBS. Isolation periods (the time when treated sheep should not be mixed with uninfested untreated sheep) can vary, according to the label instructions. They are 3–4 weeks for IGR products.

It is important too that lambs at foot should be treated with their mothers. Lice can pass from the ewes to their lambs. Lambs, in turn, can pass lice back to their mothers (and other ewes) as the ectoparasiticide concentration declines in the ewe's fleece. IGR pour-on (backline) products take several weeks to spread around the sheep, so there can be live lice present for up to 6 weeks following treatment, which will infest lambs if they are born within this time. To reduce the risks of lice being transferred from ewes to lambs, at least 6 weeks should elapse between treating pregnant ewes with an IGR and lambing. However, some products cannot be used in late pregnancy (Cotter, 2010). Similarly, treated rams should not be put out with the ewes within 6 weeks of louse treatment or lice can spread to the ewes.

If ewes are dipped during early pregnancy, the risk that they will still be louse infested at lambing is reduced, as is the chance of lambs becoming infested. Dipping young lambs results in the flock getting as close to louse free as possible. The ewe lambs, when old enough to be mated, should not then be in a position to readily infest their progeny. This could lead to a situation where dipping is only necessary every alternate year, or at even longer intervals, assuming that there is a residual louse population, and provided that dipping is carried out correctly.

NON-CHEMICAL CONTROL OF *BOVICOLA OVIS*. A number of 'non-chemical' 'husbandry' treatments have been assessed in New Zealand for the control of *B. ovis* on sheep (Heath *et al.*, 1995b). Shearing can account for a 35.7%–66.3% reduction in mean louse counts. Wetting, either with water alone or with water with added detergent, can account for a 26.9–35.3% reduction in lice. The combined effects of shearing and wetting, as opposed to shearing alone, were statistically significant on two out of three farms 32–35 days post-treatment. The effects persisted for the duration of the study (between 48 and 52 days), at which point shearing and wetting with detergent provided 95.3–99.6% control of lice (Heath *et al.*, 1995).

The red louse of angora goats (Bovicola limbata)

Shower dips and jetting races have been used for controlling ectoparasites of angora goats (Wilson *et al.*, 1978), but the wetting of animals with high volume sprays in cold,

windy weather may also predispose to pneumonia. Pour-ons containing the SPs deltamethrin or fenvalerate (2.0%) have been shown to be effective against *B. limbata*, as have pour-ons containing the IGRs diflubenzuron (2.0%) and triflumuron (Fuchs and Shelton, 1985).

Correct timing is essential for the control of *B. limbata*. As for *B. ovis* infestations of sheep, pour-ons are generally more effective immediately after shearing (Medley and Drummond, 1963; Chamberlain and Hopkins, 1971), and goats may need several treatments between shearings, at approximately 6 monthly intervals (Darrow, 1983). Kids can be infested with *B. limbata* within 2 days of birth. Thus, another critical time for treatment is before kidding (Fivaz *et al.*, 1990). Observations in Britain have suggested that SP pour-ons offer only temporary control of *B. limbata* on angora goats (Bates *et al.*, 2001a). The pharmacokinetics of sheep pour-on formulations are different on goats with short hair – as opposed to short wool, and also on goats with long fibres (e.g. angora goats). Deltamethrin sprayed along the sides of the animals was as effective as a deltamethrin pour-on.

The chewing louse of meat or dairy goats (Bovicola caprae)

In Australia, pour-on products containing deltamethrin are registered for the control of lice on goats at a dose rate of 2ml/10 kg body weight, using an approved applicator to administer a long stripe along the backline. Repeat treatment is necessary according to the label instructions (North, 2004). Unlike chewing lice on sheep (*B. ovis*) and angora goats (*B. limbata*) there is no need to shear dairy goats infested with *B. caprae* before treatment. Pour-ons containing the OPs malathion or chlorfenvinphos, and the SP cypermethrin, have also been shown to be effective against *B. caprae* on dairy goats (Taylor *et al.*, 1984; Himonas and Liakos, 1989).

Linognathus *species*

Linognathus spp. can be controlled through plunge dipping in wash made from the OPs diazinon or phoxim (sebacil), or the SP cyhalothrin. *Linognathus* spp. can also be controlled by administering diazinon or fluorosilicate dipwash by hand jetting. A consequence of dipwash not adhering to the non-greasy hair commonly found on the face or legs of sheep is that a second treatment is required 17–21 days later to kill eggs that have hatched after the first treatment (Rundle and Forsyth, 1984).

Linognathus spp. are blood feeders, so the macrocyclic lactones (ivermectin, doramectin, moxidectin) and closantel (Butler, 1986) are effective when administered either by injection or by oral drench.

Flies

Blowfly strike

Ectoparasiticides for the control of blowfly can be either preventive or curative.

PREVENTION. Plunge dipping sheep in wash containing the OPs diazinon or propetamphos will not only cure existing infestations of blowfly larvae but will also protect against reinfestation; diazinon will protect for 18–19 weeks (Kirkwood *et al.*, 1978) and propetamphos for approximately 16 weeks (Bramley and Henderson, 1984). Under laboratory conditions, shower dipping sheep with 3.0 cm of fleece in diazinon (400 mg/l) gave approximately the same period of protection against blowfly strike as plunge dipping in the same wash – 18 and 19 weeks, respectively (Kirkwood *et al.*, 1978).

Pour-on formulations containing SPs are effective against blowfly strike. Pour-ons containing high-cis cypermethrin (with a high *cis:trans* isomer ratio of 80:20) will protect sheep against blowfly strike caused by *L. sericata* for 8 weeks. Deltamethrin-based spot-ons are only recommended for the cure of active strikes.

Formulations containing the IGRs cyromazine or dicyclanil only prevent blowfly strike and are not effective in curing active blowfly strike. Some IGRs (e.g. diflubenzuron) will not give immediate kill of maggots on existing strikes. However, they do

stop them from feeding so that they die within 2–3 days. Field trials in the Republic of Ireland have shown that a pour-on formulation of cyromazine can give 13 weeks protection against strike caused by *L. sericata*, and recommended retreatments at 8 week intervals in order to reduce the incidence of strike caused by *L. sericata* to zero (O'Brien and Fahey, 1991). In Australia and New Zealand, formulations of cyromazine are also applied via plunge or shower dips. Dicyclanil as a 5% pour-on is effective against *L. sericata* in the UK (Lonsdale *et al.*, 2000) and *L. cuprina* in Australia (Bowen *et al.*, 1999). Trials in an environment house in Australia demonstrated that jetting sheep with dicylanil, or the use of a ready-to-use 5% spray-on formulation, provided over 22 weeks and 33 weeks protection against *L. cuprina*, respectively (Bowen *et al.*, 1999). In the UK, dicylanil pour-ons protect against *L. sericata* for 16 weeks.

The ML ivermectin has also been shown to protect against *L. cuprina*. In studies in an insectary using laboratory-reared *L. cuprina*, sheep that were hand jetted with an ivermectin jetting fluid (diluted to 0.03 mg/ml) were protected against induced breech and body strikes for 18 weeks (Thompson *et al.*, 1994b). Under field conditions, hand jetting reduced the incidence of strike by 93% over a 12 week period. Also, under field conditions, administration of an ivermectin jetting fluid (diluted to 0.03 mg/ml) through an AJR reduced the incidence of strike by 84% over a 12 week period (Thompson *et al.*, 1994a). At 12 weeks, there was a 90%, 86% and 93% reduction in poll, body and breech strikes, respectively, when hand jetting was used, whereas when ivermectin jetting fluid was administered through an AJR, poll, body and breech strike were reduced by 84%, 81% and 79%, respectively (Thompson *et al.*, 1994a).

The efficacy of the phenylpyrazole fipronil and the pyrethroid beta-cyfluthrin on larvae of *L. sericata* have been assessed using *in vitro* bioassays. The LC_{50} for beta-cyfluthrin was 1.56 mg/l, with little activity below 0.5 mg/l. The LC_{50} for fipronil was 0.14 mg/l, with some mortality recorded at 0.05 mg/l, and 100% mortality recorded at a concentration of 0.5 mg/l (Smith *et al.*, 2000a).

In Australia, McKenzie and Anderson (1990) showed that early treatment with diazinon and cyromazine can reduce the relative numbers of *L. cuprina* and the prevalence of strike. Similarly, in the UK the strategic administration of cyromazine shortly before the predicted spring emergence of *L. sericata* can significantly reduce *L. sericata* populations throughout the subsequent summer (Wall *et al.*, 1995).

Like the ectoparasiticide formulations for the cure chewing lice (*B. ovis*) the efficacy of formulations with a claim to protect against blowfly strike depends on wool length, and classification as off-shears, short-wool (1.0–1.5 cm) or long-wool (above 1.5 cm).

Off-shear treatments. Preventive treatments applied to off-shears include pour-on formulations containing the IGR dicyclanil or the SP high-cis cypermethrin.

Short-wool treatments. Short-wool preventive treatments include plunge or shower dipping in OP formulations (diazinon, diazinon + rotenone + PBO or propetamphos) or IGRs (diflubenzuron).

Long-wool treatments. Long-wool preventive treatments include pour-on or spray-on formulations of IGRs (cyromazine, dicyclanil, diflubenzuron), and AJR or hand-jetting formulations of IGRs (cyromazine, diflubenzuron), MLs (ivermectin), OPs (diazinon, propetamphos) or spinosyn (spinosad). Spinosyn formulations are licensed in Australia and New Zealand and provide 4–6 weeks protection against *L. cuprina*. This treatment has the advantage that it has zero meat or fleece withholding periods. Ivermectin CRCs have been shown to be 86% effective against *L. cuprina* breech strike (but only 27% effective against body strike).

Organic sheep producers in the UK can use IGRs prophylactically as part of an FH&WP where there is a risk of blowfly strike and evidence of actual risk (i.e. veterinary declaration). Cyromazine is permitted without prior permission from a UK organic certifying body. However, dicyclanil requires prior permission.

CURATIVE TREATMENT. Blowfly treatments should stop damage to the sheep, kill all larvae so as to prevent resistance and reduce future blowfly populations, and prevent restrike on the dressed area for sufficient time for the wound to heal (Levot, 2009e). Struck wool and a 50 cm barrier around the strike lesion should be shorn close to the skin before a dressing is applied. This removes many larvae (maggots), opens the struck area so that all maggot trails are found, helps to dry the area and ensures that less wool is treated with ectoparasiticides. Wool clippings should be placed into a plastic bag and sealed to kill the maggots (Levot, 2009e). However, shearing the strike area increases the workload and leaves holes in the fleece. Consequently, farmers are often reluctant to shear strikes and invariably miss some maggot trails and pour more ectoparasiticide into the fleece (Levot, 2009e). Clipping to skin level is essential. Results of a study in Australia in which the strike lesion was clipped with a mechanical shearing handpiece, but otherwise untreated, demonstrated that only four strikes out of 52 (8%) still contained larvae 1 day later. In a separate study, six out of 17 (35%) strikes remained unresolved if hand blades had been used (Levot, 2009e).

OPs will kill most maggots on existing strikes but will only provide very limited protection (2–4 weeks) against new strikes (Wilson and Armstrong, 2005). Studies in Australia have demonstrated that only a few registered dressings are capable of causing greater than 50% mortality in OP-resistant larvae (Levot, 2009e). Some IGRs (e.g. diflubenzuron) will not give immediate kill of maggots on existing strikes. However, as mentioned previously, they do stop them from feeding so that they die within 2–3 days. They also provide long-term protection (up to 14 weeks) against new strikes and pose less of a residue problem than OPs (Wilson and Armstrong, 2005).

Screw worms

Screw-worm (e.g. *Wolfahrtia magnifica*) infestations can be treated with topically administered ectoparasiticides and/or mechanical removal of the larvae. However, without preventive measures, these methods require frequent animal inspections and only provide short-term protection.

Screw-worm larvae are highly susceptible to a range of ectoparasiticides (particularly in wound dressings). Among the MLs, subcutaneous injections of doramectin at 200 µg/kg body weight have been shown to be effective in controlling active screw-worm infestations on cattle, but ivermectin and moxidectin appear to be ineffective against *W. magnifica* larvae; however, doramectin has been shown to give 21 days protection against infestation (Farkas *et al.*, 1996). Pour-ons containing the SP cypermethrin can give 11 days protection (Farkas *et al.*, 1996).

Alternatively, spraying or dipping in the OP coumaphos (0.25% aqueous suspension of a 50% wettable powder) can be used for prevention. The treatment of dairy lactating animals during peak adult fly activity (May to October) with a cypermethrin pour-on every 10–15 days is also effective. Dairy non-lactating females, replacement stock and rams should be treated with subcutaneous doramectin every 20–25 days. It is also necessary to inspect animals frequently and remove and destroy any larvae (Farkas *et al.*, 1996).

*Nasal botfly (*Oestrus ovis*)*

In some countries (e.g. Australia and the UK) the discomfort and production losses caused by *O. ovis* do not justify specific treatment. Control is generally a side effect of anthelmintic treatment (Brightling, 1988). Specific treatment of livestock for *O. ovis* control is ill advised, fearing the induction of drug resistance in the more important gut helminths. In other countries (e.g. the former USSR and Mongolia), where *O. ovis* is considered an important parasite, animals are treated specifically for oestrosis (Bukshtynov, 1975; Ilchmann *et al.*, 1986). Methods employed have included aerosol inhalation of the OPs trichlorfon or dichlorvos in sealed buildings for 1–6 h (Moiseer *et al.*, 1990), or the administration of trichorfon via twin jet irrigators into each nostril,

but individual treatment was found to be too costly and time-consuming (Bukshtynov, 1975). Horak and Snijders (1974) showed that helminth-free sheep dosed with rafoxanide remained free from infestation and showed a decrease in nasal discharge and an increase in weight gain, compared with untreated controls.

Current methods of controlling *O. ovis* in sheep are based upon the salicylanilide closantel and the MLs doramectin, ivermectin or moxidectin, administered by oral drench, CRC or subcutaneous or intramuscular injections (Roncalli, 1984; Schindler *et al.*, 1986; Dorchies *et al.*, 1989; Alzieu and Chiarisoli, 1990; Puccini *et al.*, 1993). Closantel, at a dose rate of 10 mg/kg, has been shown to be 97.7% effective at protecting against *O. ovis* and 100% effective in curing existing infestations (Dorchies *et al.*, 1997). Ivermectin administered orally at a dose rate of 0.2 mg/kg body weight has been shown to be 98–100% effective in curing existing infestations (Dorchies *et al.*, 1997; Lucientes *et al.*, 1998); however, sheep need to be treated twice (with an interval of 60 days) during the *O. ovis* season (Dorchies *et al.*, 1997). Subcutaneous injections of ivermectin (200µg/kg body weight) have been shown to be 62.5% effective in protecting sheep against attack by *O. ovis* and 100% effective in curing existing infestations (Dorchies *et al.*, 1997).

*Goat warbles (*Przhevalskiana silenus*)*

Single injections of the ML ivermectin (1.0%) at 50, 100 or 200µg/kg body weight have all been shown to be effective against *P. silenus* (Tassi *et al.*, 1987).

*Keds (*Melophagus ovinus*)*

Plunge dipping in wash containing the OPs phoxim (sebacil) or propetamphos have been shown to be effective against keds (Stendel, 1980; Bramley and Henderson, 1984), with propetamphos protecting against reinfestation by *M. ovinus* for 16 weeks (Bramley and Henderson, 1984). Pour-on formulations containing SPs are also effective against *M. ovinus* (Kettle *et al.*, 1983).

Unlike chewing lice, adult keds are mobile in the fleece (Graham and Taylor, 1941), which increases the possibility of them coming into contact with ectoparasiticide, even if it is unevenly distributed, particularly when administered via a shower dip, jetting or pour-on. However, *M. ovinus* pupae, which are immobile, may be unaffected unless the ectoparasiticide is long acting.

A single subcutaneous injection of the ML ivermectin at 200µg/kg body weight (Molina and Euzeby, 1982) or 300µg/kg body weight (Roberts *et al.*, 1998) has been shown to be effective in eradicating *M. ovinus*.

Biting and nuisance flies

Permethrin-based plunge dips are effective for only 3 weeks and diazinon dips do not last long enough on short head hair to be protective against biting and nuisance flies, and the flies do not alight on stock long enough for ectoparasiticides to be effective. Headfly (*Hydrotaea irritans*) damage can be prevented using an SP pour-on administered to the poll of the head using a T-bar nozzle.

Fleas

Dipping and spraying with the ML ivermectin have been shown to be effective against fleas infesting small ruminants (Kusiluka and Kambarage, 1996).

Ectoparasiticide Resistance

The WHO Expert Committee on Ectoparasiticides (WHO, 1957) defined (ectoparasiticide) resistance as: 'the development of an ability in a strain of insect (mite or tick) to tolerate doses of toxicants (ectoparasiticides/acaricides) which would prove lethal to the majority of individuals in a normal population of the same species'. This ability is heritable. Another practical definition of resistance is 'a decreased susceptibility of an ectoparasite to an ectoparasiticide (insecticide or

acaricide) at concentrations on or above a defined threshold concentration'. The defined threshold concentration is the dose stipulated and maintained by the instructions for use, printed on the product label (e.g. the maintenance concentration for plunge dips). In essence, this means that if all the manufacturers' instructions are followed to the full and the product is still ineffective, then (following the results of field investigations and controlled pen trials) the parasite can be confirmed resistant to that product.

Another definition must also be considered, that of 'tolerance'. Tolerance can be described as 'a decreased susceptibility to an ectoparasiticide/acaricide to concentrations below a defined threshold' (usually shown by *in vitro* studies). In practical terms, this can be interpreted as 'if all the manufacturer's instructions are followed to the full and the product is still effective'. Progressive tolerance may lead to resistance.

Side and cross resistance

Resistance to one ectoparasiticide may also confer resistance to another ectoparasiticide through 'side resistance' or 'cross resistance'. Side resistance is decreased susceptibility to more than one ectoparasiticide within the same group (e.g. resistance to two SPs). Cross resistance is decreased susceptibility to more than one ectoparasiticide within different groups (e.g. resistance to an SP and an OC).

Confirmation of resistance

Confirmation of ectoparasiticide resistance is through: (i) field investigations; (ii) laboratory investigations; and (iii) controlled pen trials.

- Field investigations assess whether the ectoparasiticide in question has been used correctly by the flock/herd owner.
- Laboratory investigations generally consist of *in vitro* bioassays to determine the LC_{90} (the concentration of the ectoparasiticide required to kill 90% of the suspect resistant population of ectoparasite). The resistance factor (RF) for the suspect resistant population of ectoparasite can be calculated by dividing the LC_{90} by that of a known susceptible reference isolate.
- Controlled pen trials, in which the ectoparasiticide under investigation is administered to sheep/goats infested with the suspect resistant isolate of ectoparasite, are required to confirm the results of the *in vitro* bioassays.

Types of ectoparasiticide resistance

Five types of ectoparasiticide (acaricide or insecticide) resistance have been postulated: (i) behavioural; (ii) penetration; (iii) site insensitivity; (iv) metabolic/detoxification; and (v) physiological.

Behavioural resistance

In behavioural resistance, parasite behaviour becomes modified so that it no longer comes in contact with the ectoparasiticide (avoidance) (e.g. psoroptic mites in the ears not coming into contact with plunge dipwash or only coming into contact with sublethal concentrations of the active ingredient).

Penetration resistance

In penetration resistance, the composition of the insect/mite exoskeleton becomes modified in ways that inhibit insecticide/acaricide penetration. This has been demonstrated in the house fly, *Musca domestica* (Sawicki, 1970), and in the one-host cattle tick *Boophilus microplus* (Schnitzerling *et al.*, 1982). Changes in the penetration rate have little significance because of the small differences between strains. However, O'Brien (1967) coined the term 'opportunistic factor' in the context of penetration resistance, and suggested the mechanism as having a 'multiplying effect' when acting in association with other mechanisms such as detoxification or site insensitivity.

Site insensitivity

Site insensitivity occurs when the chemical site of action for the ectoparasiticide becomes modified so as to have reduced sensitivity to the active form of the ectoparasiticide.

Metabolic resistance/detoxification

In this type of resistance, the metabolic pathways of the insect/mite become modified in ways that either detoxify the ectoparasiticide or disallow metabolism of the applied compound into its toxic form. In general, site insensitivity or metabolic detoxification are the main resistance mechanisms in arthropods.

The detoxification of OP compounds is the only apparent resistance mechanism that has been elucidated in blowflies (Hughes and Devonshire, 1982). The enzyme carboxylesterase E_4 is known to cause resistance to a wide range of ectoparasiticides in the peach-potato aphid (*Myzus persicae*) (Devonshire and Moores, 1984). Techniques have been developed to investigate total esterase activity using the whole homogenate of a single aphid to give a quantitative measure of esterase activity (Devonshire, 1975). In very resistant aphid populations, as E_4 contributes virtually all the esterase activity, this is the preferred method of investigation. However, in slightly resistant populations, other esterases that are common to all variants make a large contribution and can obscure the smaller differences in the amount of E_4 between resistant and susceptible aphids. In this case, electrophoretic analysis is the preferred method of investigation, as it allows isolated E_4 to be estimated from the intensity of the stained band on the gel (Devonshire, 1975; Baker, 1977). This method has enabled the quantification of the E_4 in gels by spectrophotometry (Blackman *et al.*, 1977), but it is not practicable on a large scale. The techniques described here may be of use investigating ectoparasiticide resistance in sheep or goat ectoparasites.

Glutathione S-transferases (GSTs) have been identified in 24 insect species as a polymorphic protein occurring in up to eight isoenzymes (Baker *et al.*, 1994; Yu, 1996). GSTs are used by insects and mites to metabolize xenobiotics in the body (Capua *et al.*, 1991; Yu, 1996) and elevated levels of GSTs have been shown to confer ectoparasiticide resistance in a wide variety of medical, veterinary and agricultural pests (Ibrahim and Ottea, 1995; Prapanthadara *et al.*, 1995; Yu, 1996; Bond and Bradley, 1997; Hemingway *et al.*, 1997). At present though there are no published techniques for quantifying the amounts of GSTs in sheep or goat ectoparasites.

Physiological resistance

Physiological resistance can be seen as resulting from the interplay of the other resistance factors just described (Oppenoorth, 1984).

Selection for ectoparasiticide resistance

The underlying process in arthropod resistance to ectoparasiticides is genetic selection, an evolutionary process. Selection for resistance can result from exposure to sublethal concentrations of ectoparasiticide, generally through ineffective treatment.

Milani (1954) was the first to recognize that resistance to an ectoparasiticide was mostly controlled by a single gene. Widespread use of that ectoparasiticide acts to concentrate the rare individuals carrying the resistance gene and, after a period of selection, the frequency of the resistant form in the population becomes sufficiently high to be noticed. If the continued use of the ectoparasiticide occurs after this point, the frequency of the resistant individuals will increase until they dominate the population and an altered response to a treatment will occur. This suggests that resistance in a population is the inevitable outcome of the widespread use of an ectoparasiticide.

Lice are obligate parasites, with no free-living phase, and the spread of genes between populations could be expected to occur slowly (James *et al.*, 1993). Thus, the skewed distribution of resistance between populations could be a reflection of selection occurring in only some populations of

lice and the relatively small rate of intermixing of different populations (James *et al.*, 1993). The LC_{50} values of the high virulence strains (Levot, 1992) are well outside these distributions, suggesting the emergence of a category of resistance with a different genetic basis to that previously observed (James *et al.*, 1993).

The selection pressure imposed by ectoparasiticides means that more effective control leads to more rapid development of resistance (Kunz and Kemp, 1994). In most cases then, survival following treatment is due to genetic differences rather than to escape from full exposure (Kunz and Kemp, 1994).

Development of ectoparasiticide resistance

Seven factors have been identified that aid in the development of ectoparasiticide resistance: (i) widespread use of and reliance on ectoparasiticides; (ii) ineffective treatment; (iii) prolonged exposure to a single group of ectoparasiticides; (iv) high selection pressure; (v) the method of ectoparasiticide application; (vi) ease of use in the field; and (vii) the biology of the parasite.

Widespread use of and reliance on ectoparasiticides

Ectoparasiticides should only be used if absolutely necessary and 'blanket treatment' should be avoided. Only 20% of Australian flocks are estimated to be infested with lice (*B. ovis*), yet 80% of flocks are treated for lice each year, resulting in increased costs, over-application, possible selection for resistance and/or a fleece residue risk. Effective biosecurity procedures should be the first line of defence.

Ineffective treatment

Inefficient application of ectoparasiticide has been implicated in the development of resistance in *B. ovis* (Boray *et al.*, 1988). For example, in the period July 1988 to June 1990, ectoparasiticide was applied as a backline treatment to 62% of Western Australian flocks, with 38% treated by shower dipping (Morcombe and Young, 1993). In 34.7% of these flocks, it was calculated that treatment did not eradicate lice.

Prolonged exposure to a single group of ectoparasiticides

SP pour-ons are not effective against sheep scab (Bates, 1993), and the routine use of SP pour-ons for the control of ticks, blowflies or headflies could select for resistance against SP dips, or even augment existing SP tolerance within a population. It is unwise, therefore, to treat a flock with an SP dip if SP pour-ons are routinely used.

Prolonged exposure to a single group of ectoparasiticides may therefore occur through exposure as a result of ectoparasiticide application to control a different ectoparasite. McKenzie and Whitten (1984) suggested that selection for ectoparasiticide resistance in *L. cuprina* may begin when blowfly populations are exposed to insecticidal residues in fleece following treatment for other ectoparasites. In Australia and New Zealand, many products are effective against both blowflies and lice, thus there is selective pressure on both parasites simultaneously (Sales *et al.*, 1996).

Oral anthelmintic drenches containing MLs may also select for populations of scab mites (*P. ovis*) less susceptible to the same active ingredients administered via subcutaneous or intramuscular injection. Oral ivermectin is not effective against the sheep scab mite. It reduces populations by only 40–50% (Bates and Groves, 1991), thus leaving a significant, less susceptible population of mites. Single subcutaneous injections of ivermectin can eradicate 'slow' chronic strains of *P. ovis*, or at least reduce the mite burden by 99%, whereas mite burdens of 'fast' acute strains may only be reduced by 77% (Bates, 1994). Two injections 7 days apart, as per the manufacturer's instructions, can completely eradicate all strains of *P. ovis* tested.

High selection pressure

This occurs where there is no refuge for the population exposed to the ectoparasiticide.

It is extremely important for permanent ectoparasites such as the sheep scab mite (*P. ovis*) or the chewing louse (*B. ovis*).

Method of acaricide application

Not all ectoparasiticides or their methods of application are effective against all ectoparasites (i.e. they are not all broad spectrum). This means that the ectoparasite infesting the flock must be professionally identified and the correct, licensed treatment administered (and administered correctly).

Ease of use in the field

The easier the method of application is, the more it is effective in the field.

Biology of the ectoparasite

Ectoparasites have relatively short generation times and produce relatively large numbers of offspring per generation, which means that the product label instructions must be followed. If the label states two treatments, then two treatments must be administered. The first treatment will only kill active stages of ectoparasite present on the sheep at the time of treatment. The second treatment will kill any eggs that have hatched since the first treatment. No current treatment kills the parasite in the egg (i.e. is ovicidal).

Current ectoparasiticide resistance

*Sheep scab mite (*Psoroptes ovis*)*

Strains of *P. ovis* resistant to the OC, lindane, were first reported in Argentina in 1962 (Ault *et al.*, 1962), but during the 18 years of compulsory use of lindane against sheep scab in the UK, no cases of lindane resistance were ever recorded. The OP diazinon quickly replaced lindane in the control of scab, both in South America and in the UK. Resistant strains of *P. ovis* were first confirmed in Argentina as long ago as 1970 (Rosa and Lukovich, 1970), and since then OP resistance spread throughout Argentina, primarily as a result of poor standards of sheep husbandry. In the UK, there was little chance of resistance to any ectoparasiticide developing in either scab mites (*P. ovis*) or chewing lice (*B. ovis*) during the sheep scab eradication campaign and associated compulsory dipping, owing to the 'overkill' nature of the compulsory dipping, including the supervised 'double dipping' of confirmed scab-infested flocks, and the Government Scab Approval status of the plunge dips used.

The first recorded cases of acaricide resistance in *P. ovis* in the UK (to the SP flumethrin) occurred after scab was deregulated as a notifiable disease in 1992. In 1994, two populations of *P. ovis*, from two geographically isolated areas (Somerset in south-west England, and Caithness in northern Scotland) were found to be resistant to a flumethrin-based dip, both at the recommended use rate of 44 mg/l and also at the stronger tick control rate of 66 mg/l (Synge *et al.*, 1995). Following the identification of these two isolates, a further two flumethrin-resistant strains of *P. ovis* were identified in 1995, both originating from Cumbria, in north-west England. These isolates were confirmed as resistant after extensive controlled laboratory dippings at the VLA, Weybridge. Controlled dippings were ineffective at 33.0, 44.0 and 66.0 mg/l flumethrin, although a flumethrin-sensitive population of *P. ovis* was eradicated from infested sheep at all dilutions. A lethal flumethrin concentration of above 66.0 mg/l was therefore indicated for the resistant isolates. In comparison, *in vitro* bioassays using a formulated flumethrin product demonstrated an LC_{90} of 31.72 mg/l for the sensitive population and LC_{90} values of 78.85 mg/l and 87.79 mg/l for the resistant populations, giving RFs of 2.5× and 2.8×, respectively (Bates *et al.*, 2002). Controlled dipping trials demonstrated side resistance to the SP high-cis cypermethrin (Bates, 1998). These were the first confirmed cases of acaricide resistance in *P. ovis* in the UK and in Europe. Further populations have subsequently been shown to be resistant to flumethrin by field investigations.

In the winter of 1995, a strain of *P. ovis* was isolated from a flock in the Caithness

area of Scotland that was suspected of being resistant to the OP propetamphos. Resistance was subsequently confirmed in 1996 after controlled dipping trials (Clarke *et al.*, 1996; Bates, 1998). However, controlled dipping trials also demonstrated that there was no side resistance to the OP diazinon (Bates, 1998).

The four strains of *P. ovis* resistant to the SP (flumethrin) and the one strain resistant to the OP (propetamphos) were all virulent, i.e. they covered the sheep in scab extremely quickly and produced relatively large numbers of mites. The larger the mite population at the time of treatment, the easier it is to select a subpopulation less susceptible to the treatment.

*Sheep chewing louse (*Bovicola ovis*)*

SP pour-on products for louse control were first marketed in Australia in 1981, but failure to control *B. ovis* was first suspected in the Australian louse population in 1985, and subsequently confirmed experimentally (Boray *et al.*, 1988). Resistance was understood to be the result of the overuse and/or misuse of SP products. Although products containing cypermethrin were the subject of most of the early complaints, claims that all SP pour-ons (including those applied to long-wool) and SP plunge dips were also received. Most complaints could be traced to inappropriate applications by farmers, but in an increasing number of cases resistance was implicated (Levot *et al.*, 1995). The highest RFs at this time were only 26×, but this was sufficient to prevent pour-ons from working effectively. Strains of lice with reduced susceptibility to SPs have now been reported in most states of Australia (de Clenéet *et al.*, 1989; Johnson *et al.*, 1992; Keys *et al.*, 1993). By 1991, a population from Hartley, New South Wales was found to be 642× resistant to cypermethrin, with side resistance conferred to other SPs (cypermethrin, deltamethrin, cyhalothrin and alpha-cypermethrin) (Boray *et al.*, 1988).

An *in vitro* treated surface technique that measured the response of 30 populations of *B. ovis* from New South Wales and Western Australia to cypermethrin recorded a wide variation in LC_{50} and LC_{95} values. Half the populations were considered to be pyrethroid susceptible, based on 100% mortality at 5 mg/l (or less) to cypermethrin. This suggested that factors other than pyrethroid resistance were responsible for ineffective louse control. Lice surviving 5 mg/l or greater were provisionally considered as resistant. When these individuals predominated, the proportion of lice killed by pour-on treatments was insufficient to prevent detectable infestations being present soon after treatment (Levot and Hughes, 1990). The frequency of LC_{50} and LC_{95} values was normally distributed, and it was evident that the many louse strains whose responses fell within this normal distribution were sufficient to reduce the effectiveness of backline treatments (Levot and Hughes, 1990). It was suggested that there were registered treatments that were incapable of eradicating some populations whose responses were of the top end of the normal range (Levot *et al.*, 1995). Such high-level resistant populations were the Hartley, New South Wales strain (Levot, 2000) and further high-level resistant populations from Victoria (James *et al.*, 1993) and South Australia (Wilson *et al.*, 1997).

Controlled *in vivo* pen studies demonstrated that SP pour-on treatments significantly reduced louse populations but failed to eliminate infestation in 54% of louse strains with RFs greater than 4×, using either cypermethrin or alpha-cypermethrin (Johnson *et al.*, 1992). One strain reported in New South Wales with an RF of 98× was not eradicated by dipping in SP at the currently recommended rates (Levot, 1992).

The principal effect from RFs in the field is a reduction in the effectiveness of pour-on (backline) treatments applied after shearing and as long-wool treatments. Whereas strains of lice with low LC_{50} values can be eradicated by backline treatments after shearing, eradication is less likely when more resistant strains are present (Denholm and Rowland, 1992; Keys *et al.*, 1993). The effectiveness of long-wool SP treatments can be dramatically reduced when resistant strains of lice are present,

and very often little or no reduction in lice is observed (Denholm and Rowland, 1992; Keys *et al.*, 1993). Increasing reports of SP resistance were reported in New Zealand in 1994, and low-to-moderate resistance to high-cis cypermethrin was demonstrated using a treated surface (contact) bioassay; RFs ranging from 1.0× to 12.4× were recorded (Johnson *et al.*, 1989b, 1990a). SP-resistant louse populations (particularly resistant to cypermethrin) occur throughout New Zealand, with a strong likelihood of side resistance to other SPs (Wilson *et al.*, 1997). There have been no reports of reduced efficacy to OPs in New Zealand, although there is some evidence from Australia suggesting that OP resistance may be occurring in *B. ovis* (Levot, 1994).

With an increase in the use of OPs for the control of SP- resistant lice in Australia, there was a concern over OP resistance too. A toxicological survey of 28 Australian field populations of *B. ovis* (mainly from New South Wales) identified one strain (from Orange, in central New South Wales) whose response to diazinon was recognizably separate from the normally distributed responses of the other strains; this had an RF (at LC_{50}) of about 9× (Levot, 1994). Resistance to diazinon correlated positively with side resistance to coumaphos, but there was no side resistance to propetamphos. Diazinon could therefore be recommended for the control of SP-resistant *B. ovis*, and an SP or propetamphos could be recommended to control a diazinon-resistant population (Levot, 1994).

Confirmation of SP-resistant *B. ovis* in the UK was only a matter of time. The identification of the *kdr* gene as playing a role in the genetic evolution of resistance to OC insecticides (particularly DDT) has since been found to provide certain insects with protection against pyrethroids (Levot, 1993). The intensive use of lindane plunge-dip formulations in the UK between 1945 and 1953, and between 1973 and 1984, for the compulsory treatment of sheep scab, and the popularity of lindane, DDT and dieldrin between 1953 and 1972 as plunge dips, spray races or showers for the control of blowfly strike and lice, may have already selected for resistance. Indeed, resistance to plunge dips containing lindane, aldrin and dieldrin developed in populations of *B. ovis* lice in northern England in the mid-1960s (Barr and Hamilton, 1965; Page *et al.*, 1965).

In a pilot study in the UK, four populations of *B. ovis* were assessed for sensitivity to the SPs deltamethrin, flumethrin and high-cis cypermethrin using a treated surface (contact) bioassay (adapted from protocols supplied by Gary Levot, Elizabeth Macarthur Agricultural Institute, New South Wales) (Bates, 2004). The results demonstrated a deltamethrin LC_{90} for a Devon (south-west England) isolate to be 26.4 mg/l, compared with values of 13.6, 5.6 and 2.5 mg/l for isolates from Ceredigion (south Wales), Dumfries and Galloway (south-west Scotland) and Northumberland (north-east England), respectively. Unfortunately, the lack of controlled, reliable field data (i.e. verification or authentication of both treatments and the outcome of the second treatment) rendered it impossible to confirm ectoparasiticide resistance in the Devon isolate (Bates, 2004). In March 2000, another flock, in Renfrewshire, Scotland, was suspected of being infested with an SP-resistant population of *B. ovis*. Bioassay results demonstrated a deltamethrin LC_{90} of 35.8 mg/l (RF 14.1×), greater than that of the Devon isolate (RF 10.4×). Laboratory data and reliable field data thus indicated possible resistance to deltamethrin (Bates, 2004). In November 2003, another isolate from Renfrewshire was shown to have an LC_{90} of 119.8 (RF 47.4×) and in December 2003, an isolate from Cumbria (north-west England) was shown to have an LC_{90} of 173 mg/l (RF 68.5×). Thus an LC_{90} of 25 mg/l or above is indicative of resistance to SP applied as a pour-on or spot-on in the UK (Bates, 2004).

*Goat chewing louse (*Bovicola limbata*)*

Observations in Britain have suggested that SP pour-ons offer only temporary control against chewing lice (*B. limbata*) on angora goats (Stubbs, personal communication), and apparent SP resistance to *Bovicola* lice (species not designated) was reported in two angora herds treated with a 2.5%

cypermethrin pour-on (Coleshaw *et al.*, 1992). Further studies identified the parasite as *B. limbata* (Bates *et al.*, 2001a). The result of a controlled *in vivo* trial indicated that cypermethrin pour-ons did not eradicate *B. limbata* from full-fleeced angora goats (Bates *et al.*, 2001a). However, results of *in vitro* bioassays demonstrated little difference in the relative susceptibilities to cypermethrin of *B. limbata* (LC_{50} 43.9 mg/l, range 36.5–51.3 mg/l) and a reference isolate of *B. caprae* (LC_{50} 48.1 mg/l, range 33.8–65.5 mg/l) isolated from a domestic Golden Guernsey goat that had never been treated with any SP product (Bates *et al.*, 2001a). This suggests that the failure to control was not necessarily due to ectoparasiticide resistance (Bates *et al.*, 2001). The pharmacokinetics of pour-on formulations may be different on goats with short hair as opposed to sheep with wool, and also on goats with long fibres (e.g. angora goats). Inefficacy may therefore be a case of product failure, and not of ectoparasiticide resistance as was previously recorded (Bates *et al.*, 2001a).

*Goat sucking lice (*Linognathus africanus *and* Linognathus stenopsis*)*

In South Africa, resistance to the OCs lindane, aldrin and dieldrin has been reported in *L. africanus* and resistance to the OC DDT has been reported in *L. stenopsis* (Georghiou and Lagunes-Tejada, 1991).

*Blowflies (*Lucilia spp.*)*

Resistance in the sheep blowfly *L. cuprina* to the OC cyclodiene dieldrin was recorded in Australia in 1958 (Shanahan, 1958), in New Zealand in 1961 and in the Republic of South Africa in 1964; resistance in *L. sericata* in the Republic of Ireland was recorded in 1968 (Hart, 1961). Evidence has demonstrated that resistance to dieldrin can last a long time, with resistant populations of *L. cuprina* still detectable in Australia 24 years after the widespread use of the ectoparasiticide.

OP resistance in *L. cuprina* first appeared in Australia in 1965. In South Africa, laboratory studies on the larvae of nine field strains of *L. cuprina* and one of the hairy blowfly, *Chrysomya albiceps*, showed diazinon resistance in eight strains of *L. cuprina* and in *C. albiceps*. Field evidence corroborated the presence of this resistance to current fly strike ectoparasiticides, with reduced protection resulting in the need for more frequent treatment (Blackman and Bakker, 1975). Diazinon-resistant populations of *L. cuprina* and *L. sericata* occur throughout New Zealand (Arnold and Whitten, 1976; Wilson and Heath, 1994; Wilson, 1999), with weak side resistance to other OPs. It is assumed that the *L. cuprina* strain introduced to New Zealand from Australia in the 1970s was already carrying the alleles required for resistance to diazinon (Arnold and Whitten, 1976), the basis of this resistance being the microsomal esterase E_3 (Hughes and Raftos, 1985). The result of this is that the protection periods afforded against fly strike were substantially shorter (about 75% less) than might otherwise have been expected (Levot and Boreham, 1995).

Resistance to the SP deltamethrin has also been recorded in *Lucilia* in New Zealand (Wilson, 1999). In Australia, *L. cuprina* has demonstrated resistance to carbamates (Hughes and McKenzie, 1987). Populations of *L. cuprina* resistant to the benzoyl phenylurea IGR diflubenzuron were reported in Australia 1999 and have also been recorded in New Zealand (Wilson, 1999). In some populations, this IGR resistance seems to be directly correlated with (OP) diazinon resistance (Haack *et al.*, 1999). There have been no recorded cases of OC, OP, SP or IGR resistance in *L. sericata* in the UK.

Ticks

Results of an *in vitro* micro-application bioassay to assess the susceptibility of an isolate of *I. ricinus* from north Wales demonstrated less susceptibility to diazinon than a field isolate collected from a location in the UK where ticks would not have been exposed to either OP- or SP-based acaricides. The LC_{95} for the north Wales isolate was 3816 mg/l, compared with a value of

only 480 mg/l for the more susceptible isolate (Bates, unpublished data).

Synergists and ectoparasiticide resistance

Low-level resistance to SPs can be completely suppressed *in vitro* with the addition of the monooxygenase inhibitor PPO (piperonyl butoxide) (Levot, 1995). In small-scale field trials using sheep infested with the highly pyrethroid-resistant Hartley, New South Wales strain of the chewing louse *B. ovis*, a novel experimental sheep dip formulation containing cypermethrin:PBO at a ratio of 1:5 reduced the louse population by 95% for the first 6 weeks, with the figure dropping to 80% by 10 weeks (Levot, 1995). However, mixtures of existing formulations of cypermethrin and PBO tested at the same time were poorly suited to louse control, as cypermethrin:PBO ratios of up to 1:10 did not offer much advantage over cypermethrin alone (Levot, 1995). The novel formulation of cypermethrin:PBO (1:5), which contained a wetting agent, solvent and emulsifier as well as the main constituents, provided a much greater degree of control, although this was not sufficient to make the mixture a realistic proposition for controlling highly resistant lice (Levot, 1995).

Synergists are generally applied simultaneously with the pesticide, often giving them little time to work effectively. If such synergists are allowed sufficient time to fully inhibit resistance enzymes (temporal synergism) then the sensitivity of insect pests to pesticides can be increased by several orders of magnitude (Moores *et al.*, 2005; Young *et al.*, 2005). This effect has been demonstrated in the poultry red mite (*Dermanyssus gallinae*). Suspect SP-resistant populations of *D. gallinae* were shown to have LC_{50} values of above 3000 mg/l when exposed to cypermethrin alone, but LC_{50} values decreased to 167.0 and 1061.0 mg/l when PBO was administered simultaneously. However, LC_{50} values were reduced even further (to 2.78 and 3.5 mg/l, respectively) when 100 mg/l PBO was administered 12 h before exposure to the cypermethrin (Bingham *et al.*, 2007).

On-farm ectoparasiticide resistance control programmes

These should include the following procedures:

- Permanent ectoparasites should only be treated when identified in a flock/herd (regular inspection), and effective biosecurity should be used to prevent their introduction.
- When applying an ectoparasiticide, the manufacturer's instructions for dose rate and method of application should be scrupulously followed, and the application method should be calibrated correctly and working effectively. The dose should be calculated for the largest sheep/goat for pour-ons and injections, and saturation to skin level ensured in plunge and shower dipping, AJRs and hand jetting.
- Treated and untreated animals should not be mixed. Breakdown in protective efficacy can expose chewing lice (*B. ovis*) and scab mites (*P. ovis*) to sublethal concentrations of ectoparasiticide, thus allowing them to survive and breed and possibly selected for resistance.
- A chemical from a particular group (e.g. OCs) should not be used if resistance to any other chemical from this same group has been confirmed in the flock.
- Most treatment failures are due to failure to treat every sheep correctly, not to resistance, so every other cause of failure should be eliminated before assuming resistance.
- The same product should not be used every year. Most resistance occurs where the same product group has been used repeatedly for a number of years. If treatment is necessary every year then product groups need to be rotated to avoid the build-up of resistance.
- The treatment of long-wool sheep for chewing lice (*B. ovis*) should be avoided. If used as an emergency treatment, then it must be ensured that the next short-wool treatment is from a different chemical group.

- Strategies should be based on integrated pest management (IPM) techniques, exploiting the biology of the pest, reducing selection pressure to a minimum, increasing the useful life of an ectoparasiticide and decreasing the interval of time required for a parasite to once more become susceptible to a given ectoparasiticide (National Research Council, 1986).
- If a broad-spectrum ectoparasiticide is used to control a permanent ectoparasite, an effort should be made to treat when there is no risk of accidental exposure to other, semi-permanent ectoparasites (e.g. treat for lice when blowflies are not active).
- The use of ectoparasiticide in the flock/herd should be reduced. Ectoparasiticides should only be used if absolutely necessary, and an annual 'blanket treatment' of the whole flock should be avoided. Treatment of uninfested animals is undesirable.
- Where there is no refuge for the ectoparasite population exposed to the ectoparasiticide, there is a high selection pressure. This is extremely important for of permanent parasites such as lice or scab mites.
- In an area where resistance has occurred, continued use of an ectoparasiticide may be required to control other parasites which remain susceptible. This could confound attempts at parasite management. For example, in the UK, SP pour-ons have in the past been used for the control of ticks (*I. ricinus*) in upland grazings, where *B. ovis* is also currently a serious problem. Similarly, the use of MLs as anthelmintics (as injections, or via oral dosing or slow release bolus) may select for resistance in ectoparasites (against which they have a relatively narrow range of efficacy), or vice versa (see next section).
- Variations in dose or rate of application may delay or minimize resistance by preserving a sufficient population of susceptible individuals (alleles). This can be done by using low dose rates of a given ectoparasiticide, so as not to select against heterozygotes in which resistance is recessive (National Research Council, 1986). The use of doses less than 100% effective may reduce the threat of resistance if low levels of the parasite can be tolerated (Kunz and Kemp, 1994), e.g. in meat-producing sheep infested with chewing lice.
- The excessive use of parasiticides for short-term gains may be the worst possible practice in the long term (Kunz and Kemp, 1994).
- Fewer or less frequent applications, which reduce the selection pressure over time, would decrease the rate and probability of resistance development (Kunz and Kemp, 1994).
- The simultaneous use of two or more ectoparasiticides (mixtures) with different mechanisms of action or different target site effects can be an important strategy in avoiding or maintaining resistance. However, if the parasite population is already resistant to a particular ectoparasiticide, this ectoparasiticide (even at an increased dosage) would be ineffective as part of a mixture (Kunz and Kemp, 1994). The use of mixtures must begin before resistance to one component occurs, each component must have similar decay rates and components must have different modes and sites of action, or different resistance mechanisms (Kunz and Kemp, 1994). Mixing chemicals can sometimes lead to potentiation, rather than merely to additive effects, thus delaying or preventing resistance (Kunz and Kemp, 1994).
- Not all ectoparasiticides, or their methods of application, are effective against all ectoparasites (i.e. not all are broad spectrum). The parasite infesting the flock must be professionally identified and the correct, licensed treatment administered (and administered correctly).
- Ectoparasites have relatively short generation times and produce relatively large numbers of offspring per generation.

The product label instructions must be carried out. If the label states repeat treatments, then repeat treatments must be administered. The first treatment will only kill active stages of parasite present on the sheep/goat at the time of treatment. The second treatment will kill any eggs that have hatched and/or ectoparasites coming out of moult since the first treatment.

The development of resistance to current chemical classes of ectoparasiticide presents an undeniable threat to the long-term viability of the animal health industry (Hennessey and Andrew, 1997). Alternative control strategies, including vaccines, biological control and breeding for parasite resistance, are unlikely to be widely available in the near future, and even then they will be integrated with chemotherapy (Hennessey and Andrew, 1997). The significant cost of research and development of new therapeutics for food-producing animals, together with the small market share of animal health products, are a positive disincentive for drug development. The chemical actives that are currently available are all that we are likely to have for the foreseeable future and they must be used more effectively (Hennessey and Andrew, 1997).

Ectoparasiticides available to producers will also probably be 'lost' at a greater rate than the registration of new compounds (Levot, 1993). If concerns over residues mean that consideration is given to deregistration, or to further regulation of ectoparasiticide use, producers must be provided with alternative control strategies (Levot, 1993). Rational pest control strategies are needed to manage resistance, not only to prolong the effectiveness of current ectoparasiticides, but to reduce the environmental impact of these substances (Kunz and Kemp, 1994).

Simultaneous effects of ectoparasiticides on other parasites

MLs are very effective for the control of sheep scab (*P. ovis*) and nasal botfly (*O. ovis*), and probably sucking lice (*Linognathus* spp.) and keds (*Melophagus ovinus*), but they are also highly effective anthelmintics. Every time an ML is used specifically for ectoparasite control the host's gut nematode population is simultaneously exposed to it, so the unnecessary overuse of MLs as ectoparasiticides may reduce their efficacy as anthelmintics through selection for resistance.

Some ectoparasiticides are not compatible with other veterinary medicines administered to sheep or goats. Plunge dipping in an OP (e.g. diazinon)-based dip formulation must not be carried out within 14 days of administering another OP or an imidazothiazole (e.g. levamisol)-based anthelmintic drench. Neither should shearing, bloom dipping or washing be carried out for at least 4 weeks following ectoparasiticide treatment.

Operator Safety

Ectoparasiticides are formulated to kill, therefore a distinct disadvantage of using these inherently dangerous chemicals for the control of sheep or goat ectoparasites is their adverse effects on the human operator, exposed animal life in the environment and the sheep or goat host itself.

Operator exposure during application

A consequence of the Sheep Scab Eradication Campaign in Britain between 1974 and 1992 was that sheep farmers, their families and employees, and dipping contractors were regularly exposed to high levels of the acaricides that were approved for use within the compulsory dipping periods: the OC lindane, the OPs diazinon and propetamphos, and the SP flumethrin. Although exposure to the OCs or SPs could not be classed as 'safe', the biggest concerns regarding operator exposure were directed at the OP diazinon.

OPs are acutely toxic to man because they inhibit acetylcholinesterase (Ach) at nerve synapses or the neuromuscular junction, causing 'dipping flu'; repeat exposure

to low levels of OP may lead to delayed toxicity. Between 1985 and 1996, 45.4% of Suspect Adverse Reports (SARs) received by the UK Veterinary Medicines Directorate (VMD) were related to OP exposure. Exposure to OP can be through contact with the concentrated product (primarily at make-up and replenishment), contact with made-up dipwash and exposure to sheep treated with OP dipwash. Although a relatively large number of people appear to have acute adverse reactions after working with OPs, the number of people suffering with chronic effects of OP exposure are relatively low. Genetic differences in the expression of target enzyme and/or activation and detoxification enzymes may contribute to differences in individual toxicity.

Making up a dip initially and then at replenishment is recognized as the principal source of OP exposure. In 1993, the sale and supply of OP dips in the UK was restricted to those holding a 'Certificate of Competence'. Dip concentrate could only be sold to users who had attended a government-sponsored training course and the certificated buyer had to be present at the dipping operation. A medical and scientific panel was also set up to evaluate existing research and to recommend further areas of work on OP sheep dips in relation to human exposure and the environment. A consequent recommendation of the panel was the temporary withdrawal of OP dip formulations from the British market in 2000 in order for manufacturers to improve their delivery systems. However, it was recognized that serious sheep health and welfare problems would occur if OP dips were withdrawn permanently. In 2001, it became a legal requirement in Britain to use a closed transfer system when measuring out and mixing OP concentrate. Current closed transfer systems consist either of premeasured 100 ml, water-soluble sachets or of one of two systems involving cans and pumping equipment so that the OP dip concentrate can be added safely to the dip bath. In all cases contact with the concentrate is considerably reduced.

OP toxicity was initially a British problem, probably associated with the compulsory use of diazinon during the Sheep Scab Eradication Campaign. Legislation on the use of OP dip formulations has now spread to other countries where OPs are used extensively for sheep ectoparasite control. In Australia, Occupational Health and Safety (OH&S) regulations require that employees applying chemicals are appropriately trained and supervised in their use. The Ectoparasiticides Act (1999) also requires that *all* users be trained to use chemicals and that records are kept of ectoparasiticide applications (Evans and Scanlan, 2004). Spray drift is a common problem with shower dips, as aerosol droplets are not easily seen but are readily inhaled. Increasing the height of the side panels of the dip is recommended, at least on the side where the operating valves are situated. However, in 2007, OP plunge- or shower-dipping formulations for the control of lice were phased out in Australia, owing to health concerns on worker exposure to splash and spray from dipwash, applied via these saturation methods, although pour-ons or backline treatments containing OPs are still licensed for use.

In the UK, the Health and Safety Executive (HSE) and the Department for the Environment, Food and Rural Affairs (Defra) have produced an essential guide on safe sheep dipping (HSE, 2007), describing the necessary personal protective equipment (clothing) (PPE) and engineering controls to prevent exposure to diluted dipwash. The recommended PPE should be worn at all times, but particularly when handling the concentrate and mixing the dip. Operators should wear overalls, gloves, waterproof boots and a washable hat. Waterproof trousers are recommended for those working by the dip, to avoid splashing as sheep enter or are dunked. Hands, arms and face should be washed with water after contact and especially before eating or drinking, and wet clothing should be changed as soon as possible. Care should be taken of dip splash as the sheep enter the dip bath or are dunked, and where sheep shake and spray dipwash as they leave the dip. If chemical is swallowed or contacts the eyes the Poisons Information Centre should be contacted immediately.

Pour-on products containing the OP diazinon are available in Australia but not in the UK. Care is needed during the handling and application of these OP pour-ons and protective clothing must be worn as the concentration of OP in backline treatments is much higher than in dipwash. OP backline treatments require dilution in water before use, thus extra care must be taken to avoid splash while mixing.

The handling of sheep treated with ectoparasiticides (by whatever method) should be avoided. Essential husbandry procedures (foot trimming, etc.) should be carried out before or as long as practically possible after treatment.

The fate of OP dip formulations in the UK is continually under review. However, with ML injections being the only alternative for sheep scab control, the withdrawal of OP dips could have serious sheep health and welfare implications, while reliance on the MLs could select for anthelmintic resistance in gut nematodes.

Consumer Safety

Meat

In Europe, Australia, New Zealand and most other developed countries consumer safety is ensured through the definition of maximum residue limits (MRLs) for ectoparasiticides in edible tissue in the host species, and the specification of associated withholding times for the sale of meat or milk for human consumption following treatment. The meat withholding period (meat WHP) is the minimum period of time that must elapse between the last treatment with an ectoparasiticide and slaughter for human consumption (Evans and Scanlan, 2004). Meat WHPs may vary with the method of ectoparasiticide application and with relevant national veterinary medicines regulatory authorities. In Australia, there is an additional Export Slaughter Interval (ESI), the minimum suggested time interval between treatment and slaughter for export (Evans and Scanlan, 2004).

In the UK, there are no ectoparasiticides licensed for use on sheep or goats producing milk for human consumption (NOAH, 2010). Consequently, the use of an ectoparasiticide on dairy animals for welfare reasons can result in considerable economic loss, even though the UK sheep/goat dairy industry is relatively small. In this situation, only severely infested animals should be treated and their milk stopped from entering the food chain. Other less affected animals should be treated once they are dry. In countries where the sheep/goat dairy industry is well developed, the relevant national veterinary medicines regulatory authorities should be consulted on milk withdrawal periods.

Environmental Safety

Licensed products for the control of sheep/goat ectoparasites, particularly those applied using saturation methods, can be the cause of serious environmental pollution if not used responsibly. Pollution via saturation methods can occur through three main routes, which are discussed below: (i) badly maintained dipping facilities; (ii) disposal of the spent (used) dipwash; and (iii) dipped sheep entering watercourses. Another significant source of environmental pollution is the washing of ectoparasiticide-treated greasy (raw) wool.

Badly maintained dipping facilities

Sheep dip baths were historically located close to natural watercourses, utilizing the river or stream to fill the dip bath. Leakage or splashing from poorly maintained dipping facilities have been responsible for many pollution incidents. Surveys of dipping facilities in Wales and Scotland have demonstrated that 26% and 69%, respectively, were at high risk of causing pollution, and farmers had a complete lack of appreciation of the acute ecotoxicity of SP dips. Dipping set-ups should be inspected regularly for cracks and leaks, and new set-ups should never be located next to watercourses.

Disposal of spent dipwash

SP plunge-dip formulations are relatively safe to the operator compared to OP formulations, but they are one hundred times more toxic to the environment, especially to aquatic invertebrates.

Historically, spent dipwash was released into the environment after dipping by opening a drain plug at the bottom of the dip bath. Equal numbers of farmers in Northern Ireland emptied the dip bath immediately after use (when the dipwash was still relatively strong), compared with those who allowed the dip to stand some time before emptying. Tanks with drain plugs were more likely to be emptied immediately.

Later recommendations for dip disposal included disposal on to land of minimal agricultural value ('sacrificial land') provided that it could absorb the volume applied to it without the contamination of adjacent groundwater and drainage systems. In 1997, there was an upsurge in water pollution incidents in the UK associated with sheep dipping, particularly in Wales and northern England, with SP dips the main culprits. In 1998, the Certificate of Competence Scheme, initiated for the sale of OP dips (with respect to operator safety), was extended to include SP dips. The current EU Groundwater Directive stipulates that farmers wishing to dispose of spent sheep dip on to land that might lead to a direct pollution incident now have to apply for a licence or hire a contractor to remove the spent dipwash; both alternatives could be expensive. In 2006, the UK VMD placed a ban on the manufacturing of SP dips. SP dip formulations were only to be allowed back on to the market if eco-friendly formulations could be developed. To this date [2012], no SP plunge dip formulation has returned to the UK market.

Mobile dip baths, showers or jetters should also be set up well away from watercourses or main drains. If a mobile dipping contractor is used and takes away the spent dipwash to his site, he must possess a suitable Groundwater Authorisation. Methods have been developed to degrade OP and SP dipwash (e.g. the addition of agricultural soaked lime to flumethrin (SP) wash and of hypochlorite to propetamphos (OP) wash). Products are now available containing enzymes derived from soil bacteria that can break down diazinon dipwash to a safe disposable liquid. Diazinon can be degraded by 99.9% after 3 h, and be totally undetectable after 3 days. A large amount of contaminated organic matter in the dip bath can be contaminated with ectoparasiticide. Sweepings of contaminated organic matter from the draining pens and kemp, fleece and faeces regularly removed from the dipwash must be disposed of in a way that does not contaminate the environment.

Direct pollution from dipped sheep

Freshly dipped sheep entering a watercourse are considered to be another major source of pollution. The environmental effects of SP (and to a lesser extent OP) ectoparasiticides washed out of the fleece of dipped sheep by swimming or fording rivers directly after dipping is a serious problem, which is significantly increased by the number of dipped sheep involved. For example, although flumethrin concentrations in the fleece degrade from 66 to 19.1 mg/l in shorn fleece, and to 26.4 mg/l in unshorn fleece 70 days after dipping, ectoparasiticide washed out of fleece at these concentrations may still have significant effects on aquatic life if dipped sheep are forced to ford or swim watercourses. In the UK, Environment Agency advice is to allow dipped sheep to stand in the draining pen for at least 10 min to catch and return any run off to the dip bath. In addition, they must not return to their normal grazing, but be held in a holding field (with no natural watercourses) next to the dipping set-up, with a trough of fresh water, for a minimum of 24 h. If there are natural watercourses in the holding field, they must be fenced off from livestock access. This can be achieved using electric stock fence. The holding period will allow sheep to dry out before moving on.

In Australia, diflubenzuron is considered safe and effective if administered correctly and at the right time after shearing. However, spent dipwash can remain active in the soil for several months.

Pollution from wool processing

Ectoparasiticides applied by saturation methods or by pour-on can result in high residues in the fleece. Some ectoparasiticides, e.g. the IGRs diflubenzuron and triflumuron, can have extremely high fleece residues. Fleece ectoparasiticide residues are essential in order to cure existing ectoparasite infestations and remain long enough in the fleece to not only kill ectoparasites emerging from eggs or pupae but to protect against infestation or reinfestation from other untreated sheep or from ectoparasites in the environment. This length of protection is particularly important in the prevention of blowfly strike.

However, these chemical residues in the fleece are a threat to international markets for raw wool. Pollution and environmental controls in many wool-processing countries are becoming increasingly stringent. To avoid the possibility of restrictions and regulations being imposed on the marketing and processing of exported wool, the wool industry needs to voluntarily reduce the level of chemical residues in greasy wool. 'No-chemical' or 'low-chemical' residue wools may have a significant market advantage. This marketing incentive is very important for the Australian wool industry: being able to provide a residue-free product would give Australian wool a marketing advantage.

A recent Australian Wool Industries annual survey of fleece ectoparasiticide residues showed that OP and SP residues in the national clip are steadily declining, with mean residues for each class now less than 2 mg/kg greasy wool. Cyromazine residues fluctuated between 5 and 10 mg/kg greasy wool, depending on seasonal conditions and the prevalence of blowfly strike. Dicyclanil residues were low but increasing, with mean residues during 2000/1 at 0.4 mg/kg greasy wool.

A recent survey into ectoparasiticide residues in British wool conducted by the British Wool Marketing Board (BWMB) suggested that 10% of the UK clip had higher residues than acceptable (e.g. above 300 mg/l). Despite improved efficiencies at effluent treatment plants, monitoring by the Environment Agency has frequently shown excess levels of residue in discharges by the textile industry when wool is scoured, and also further down the processing route at dye houses. The EU imposes an 'Eco-Label' for textiles that considers the overall environmental impact of processing a woollen garment. It sets ectoparasiticide residue limits for raw wool of 2 mg/kg for OPs and 3 mg/kg for SPs. There is equal emphasis on certifying a clean production pipeline, with limits on effluent discharge from scouring, shrink proofing and dyeing sites.

In Australia, there was previously a wool withholding period (wool WHP) for all ectoparasiticide formulations, which has now been replaced by a Wool Harvesting Interval (WHI) and a Wool Rehandling Period. The WHI is the time required to elapse between treatments with ectoparasiticides and shearing (or crutching), when the wool is able to be harvested and satisfy Australian environmental requirements. It is also important for the occupational health and safety of shearers and wool handlers (Evans and Scanlan, 2004). In the UK, it is recommended that 'good husbandry practice' is adopted by the sheep industry by avoiding dips or pour-ons within at least 3 months of shearing/slaughter.

It is not advisable to shower or plunge dip sheep with more than 6 weeks of wool growth. Ectoparasiticides applied to sheep with greater than 6 weeks wool growth will leave an unacceptable residue in greasy wool at the next shearing. Where chemicals are applied within 6 weeks off-shears for lice (*B. ovis*) control, only minimal residues remain at the following shearing.

All this is not to say that chemicals should not be used at all. All registered products can be applied to sheep provided they are used according to the manufacturers' instructions. Producers must take advantage of IPM, and utilize non-chemical alternatives

and limit chemical treatments to situations in which no alternative exists.

Macrocyclic lactones (MLs)

There is some evidence that the MLs administered by oral drench or injection and voided with the host faeces on to pasture can adversely affect the normal arthropod fauna associated with faecal decomposition. McKeand *et al.* (1988) observed that the diameter, depth and weights of faecal 'pats' from cattle receiving an ivermectin pour-on (500µg/kg body weight) were similar to pats from untreated cattle. However, sublethal effects of the MLs can be as serious as those of acute toxicity (Strong *et al.*, 1993). *In vitro* laboratory studies have demonstrated that cattle dung concentrations of above 0.015mg/l ivermectin reduced pupation in the yellow dung fly (*Scatophaga stercoraria*) by 50%, and that a concentration of 0.001% prevented adult emergence by 50%. Where batches of *S. stercoraria* larvae were reared in dung containing as little as 0.0005 mg/l ivermectin, emerging adults showed developmental abnormalities in wing morphology (Strong *et al.*, 1993).

Sheep dung containing ivermectin (following oral drenching) has also been shown to cause significant mortality to newly emerged larvae of the bush-fly (*Musca vetustissima* Walker) up to 1 week post-treatment (Wardhaugh *et al.*, 1993). Insects feeding on the dung of ivermectin-treated sheep displayed adverse effects similar in range to those reported in cattle dung. However, their duration was much more transient, owing probably to differences in drug formulation and route of administration (Wardhaugh *et al.*, 1993).

Other Factors Affecting Choice of Ectoparasiticide

Size of flock

The time and cost of using a particular product must be considered: time must not be underestimated, and inaccurate application at the expense of speed must be avoided. All contact sheep have to be treated, not just those presenting with clinical signs. To save time, sheep and goats should be mustered/housed on the day before treatment.

Physiological condition of the sheep

The product must be suitable for the age of animal being treated. Some application methods (e.g. plunge dipping) can be stressful to in-lamb ewes. Studies have shown that plunge dipping in water alone was more stressful than receiving a pour-on, but was less stressful than dipping in an ectoparasiticide formulation. Thus the nature of the active ingredient itself causes a reaction above that experienced by the dipping process. In addition, stress recorded before treatment indicated that sheep were also stressed through the smell and sight of the dip bath. Some treatments are not advisable for young lambs. Rams and fat sheep are susceptible to 'immersion shock' while plunge dipping, and fatalities can occur. Choice of a treatment may therefore depend on how close finished lambs or cull ewes are to market.

Availability of labour and facilities

Some treatments require extra labour, fixed equipment and waste disposal. Some of this will have to be hired – is it affordable for the full time required? Is mobile equipment (races, etc.) available? Is there a good set-up site with regard to effectiveness, health and the environment?

Weather

Plunge and shower dipping should be avoided in extremes of hot or cold as well as in wet weather. Sheep should not be plunge dipped, shower dipped or receive a pour-on while wet or during wet weather. Hypothermia can occur if sheep are plunge dipped late in the day if the weather is cold.

Allow enough time for dipped sheep to dry out before nightfall.

Organic producers in the UK

Non-organic (conventional) sheep/goat producers have a variety of synthetic chemical (allopathic) medicines to control ectoparasites (Bates, 2009c). Under organic standards, the use of homeopathic or herbal preparations is recommended in preference to allopathic medicines. However, the use of allopathic medicines is allowed to avoid suffering and distress and where homeopathic preparations would be ineffective (Soil Association, 2009).

Only ML injections are currently approved by UK Organic Standards for the control of sheep scab (*P. ovis*), but only if described in the FH&WP under derogation from the organic certifying body and with a plan to reduce future reliance. SP pour-ons/spot-ons (alpha-cypermethrin, cypermethrin and deltamethrin) are all approved in the UK by the Soil Association for the control of lice (*B. ovis*) and the prevention of blowfly strike. IGRs can be used prophylactically as part of an FH&WP where there is a risk of blowfly strike and evidence of actual risk (i.e. by veterinary declaration); cyromazine is permitted without prior permission from a certifying body, but dicyclanil requires prior permission. OP dips are totally prohibited and organic certification will be withdrawn if they are used.

A range of herbal repellents are available in the UK for short-term (environmentally safe) protection. Essential oils (citronella, lavender)-based repellents are also available, all approved by the Soil Association. These are 'approved' by the UK HSE under the Biocidal Products Directive as repellents, but not as animal medicines.

Table 9.6. Calculation of organic meat withdrawal periods (MWPs) in the UK (Source: Soil Association, 2009).

Conventional MWP (CMWP) (days)	Organic MWP (days)
None described	2
0–2	7
2–8	3 × CMWP
19–28	56
29+	2 × CMWP

Table 9.7. Ectoparasiticide meat withdrawal periods (MWPs) (days) for organic sheep flocks in the UK.

Active ingredient	Conventional	Organic
Doramectin (ML)[a]	70	140
Ivermectin (ML)	42	84
Moxidectin (ML)	70	140
Moxidectin LA (ML)	104	208
Alpha-cypermethrin (SP)[b]	28	56
Cypermethrin (SP)	8	24
Deltamethrin (SP)	35	70
Dicyclanil (IGR)[c]	40	80
Vetrazin (IGR)	3	9

[a] ML, Macrocyclic lactone; [b] SP, synthetic pyrethroid; [c] IGR, insect growth regulator.

Meat withdrawal periods (MWPs) are a significant issue for organic producers in the UK (see Tables 9.6 and 9.7), as they are considerably longer than those defined for conventional producers.

There are also issues for the administration of allopathic veterinary medicines. Organic status can be lost if lambs (below 1 year old) receive more than one course of treatment before slaughter and if an adult sheep receives more than three courses of treatment in one calendar year. However, antiparasitics and compulsory eradication campaigns are exempt from these rules.

10

Alternative Control Methods

Ectoparasite control has relied heavily on chemicals (ectoparasiticides) for more than 100 years. However, issues such as the toxicity of ectoparasiticides to humans (particularly the organophosphates), and increasing environmental concerns about the persistence of chemical residues in wool and the disposal of spent dipwash have stimulated active interest in the 'non-chemical' control of ectoparasites.

The development of resistance to current chemical classes of ectoparasiticide also presents an undeniable threat to the long-term viability of the animal health industry. Furthermore, the chemical actives that are currently available are all that we are likely to have for the foreseeable future and they must be used more effectively (Hennessey and Andrew, 1997). The sheep and goat industries are therefore under increased pressure to reduce their use of chemicals. There is a clear incentive for alternative strategies – such as biocontrol methods – to be developed. These include such areas of interest as the potential for new natural (plant derived) ectoparasiticides, ectoparasite vaccines, biological control (biocontrol), trapping, sterile (male) insect release techniques and breeding of the host for ectoparasite resistance.

New Natural Ectoparasiticides

Many familiar active ingredients used in ectoparasiticides for the control of sheep or goat ectoparasites (e.g. derris, pyrethrum, rotenone and tobacco) were originally derived from plant material. New natural plant derivatives (particularly oils) are being investigated for their ectoparasiticidal efficacy as well. Plant oils are largely low-molecular weight terpenoids, which have a high margin of safety for the treated animal and animal handler, and no environmental toxicity.

Neem oil (from the neem tree, *Azadirachta indica*) has been shown to have ectoparasiticidal properties, and if formulation problems can be overcome may have great potential for the future. However, O'Brien *et al.* (2000) observed that neem oil had no effect against the sheep scab mite (*Psoroptes ovis*), although it has been reported to be highly effective against sheep ear mites (*Psoroptes cuniculi*) and has some efficacy against the itch mite *Sarcoptes scabiei* var. *ovis* (which causes sarcoptic mange).

Perrucci *et al.* (1994) assessed the *in vitro* efficacy of lavender (*Lavandula angustifolia*) essential oil, and of some of its main constituents – linalool (an alcoholic monoterpenoid), linalyl acetate and camphor, against *P. cuniculi* in the rabbit. Lavender

essential oil was 100% effective at concentrations between 0.25 and 6.0 µl/ml after 24 h. Similarly, linalool was effective at concentrations between 0.18 and 6.0 µl/ml after 24 h. Linalyl acetate and camphor were effective only at concentrations above 2.0 µl/ml after 24 h (Perrucci *et al.*, 1994). The biological activity of essential oils is mostly due to the monoterpenoids present in the oil, and linalool was further investigated in the treatment of otitis caused by *P. cuniculi* in the rabbit and in the goat by Perrucci *et al.* (1997), who showed that 3% and 10% linalool gave 80% and 100% efficacy, respectively.

A series of *in vitro* and *in vivo* assays were conducted by Wall and Bates (2011) to examine the effects of a *trans*-cinnamic acid ethyl ester (from the cinnamon tree, *Cinnamomum camphora*) on *Psoroptes* mites. *In vitro* exposure to the test material at concentrations of 10, 1 or 0.1% (v/v) gave 100, 74 and 20% mortality, respectively, after 24 h, with an LC_{95} of 6.29% (95% confidence interval 4.98–8.88). *In vivo*, *trans*-cinnamic acid ethyl ester suspended in 2% w/v lecithin was 87.5% effective in curing active sheep scab caused by *P. ovis* when applied as a spray formulation. These data suggest that, with appropriate development of suitable application technology, linalool or *trans*-cinnamic acid ethyl ester may have a role as potential therapeutic treatments for active sheep scab.

Other plant extracts (e.g. of garlic – *Allium sativum*, cedar – *Cedrus deodara*) have shown some efficacy, either individually or as combinations, against *P. cuniculi* and *S. scabiei* var. *ovis*, *S. scabiei* var. *caprae*, with some effect against *Demodex caprae* (the causative organism of goat mange).

Ectoparasite Vaccines

The immunological control of sheep ectoparasites (scab mites, chewing lice and blowflies) is currently being investigated, and although initial results are promising, licenced products for on-farm use are still a long way off. Vaccines must be as effective as current chemical ectoparasiticides and of similar cost. If they are not 100% effective, they may render infestations subclinical and chemical ectoparasiticides will not only be required to control other ectoparasites, but also the infestations that have been rendered subclinical by the vaccines. The frequency of administration that vaccines might require must also reflect husbandry practices.

Tick vaccines

An effective cattle tick vaccine has been developed against the one-host cattle tick *Boophilus microplus*, and has been available commercially in Australia (as TickGARD™ or TickGARD plus™) and Latin America (as Gavac™) for a number of years. The vaccine consists of a single recombinant antigen (Bm86) – a membrane-bound glycoprotein localized to the surface of the digestive cells of the tick gut – against which the vaccinated host produces antibodies. Bm86 antibodies ingested by the tick bind to its gut, resulting in lysis and increased leakage of gut material into the tick's haemolymph. This kills feeding and detached ticks, and initiates a strong inhibition of oviposition in surviving ticks. Numbers of engorged female ticks can be reduced by 40% (Massard *et al.*, 1995) and the weights of surviving adult ticks are reduced by 30% (Khalaf-Allah, 1999).

Sheep scab (*Psoroptes ovis*) vaccines

Sheep scab is a form of allergic dermatitis initiated by the excretory/secretory products of the mite *P. ovis*. The heat and humidity produced by the inflammation forms the microclimate required for mite survival, and the leakage of serous exudate forms the basis of the mite's nutrition (Bates, 1992b). Mites graze the skin around the moist periphery of the lesion, taking in nutrients with the serous exudate, skin secretions and lipid. Mathieson (1995) confirmed

experimentally that *P. ovis* ingests serum components likely to be present in the surface exudate associated with clinical sheep scab. Wikel (1988) stated that in developing a tick vaccine it was important to avoid the induction of intense host skin reactions to tick feeding through the use of salivary gland derived molecules. A similar assumption can be applied to a vaccine against sheep scab. The very fact that scab is a form of allergic dermatitis suggests that conventional theories for vaccine development could increase the severity of disease and not reduce it.

The method adopted for the development of the *B. microplus* tick vaccine was to direct immunological control to 'hidden' or 'concealed' antigens. Concealed antigens do not stimulate an immune response during a natural parasite infestation, typically because of their physical location. Despite this characteristic, a parasite can be damaged by the immunological response produced in vaccinated animals. The concealed antigen is recognized by antibody and other effector components of the host's immune system that are contained in the parasite's meal (Willadsen *et al.*, 1993). Immunity to concealed antigens has two distinct advantages. First, as the tick antigen is not normally encountered by the host, it stimulates a different immune effector mechanism, and this immunity can be co-expressed with naturally acquired immunity in a single host. Secondly, because the antigens being used are normally 'concealed' from the host, it seems unlikely that the parasite will have developed a sophisticated means of evasion of an immune attack on them (Willadsen and Kemp, 1988).

Observations on cattle infested with *P. ovis* have shown that as the lesion progresses, specific serum antibody activity appears, mite populations decline, the lesions resolve and specific serum antibody activity also declines (Fisher and Wilson, 1977). Similar studies on sheep have shown circulating IgG increases steadily until treatment (Bates, unpublished data).

Watson *et al.* (1992) demonstrated that immunoglobulin against the Australian blowfly (*Lucilia cuprina*) can be secreted on to the skin in concentrations comparable to circulating levels, and postulated that this may mediate immunological protection against *L. cuprina*. Similarly, if effective skin concentrations of anti-*P. ovis* immunoglobulins are produced during active sheep scab, these may also be effective against *P. ovis*. Stromberg and Fisher (1986), investigating *P. ovis* infestations of cattle, suggested that mite-specific immunoglobulin and leucocytes attack the midgut cells of the mite. The gut of many arthropods is lined with a peritrophic membrane (PM) that separates digested food from the gut epithelium (Eisemann and Binnington, 1994). In astigmatid mites, the PM 'buds off', forming an envelope around the mite faeces. Thus, in psoroptic mange in cattle and in sheep (sheep scab), immunological attack is initiated by the PM-enveloped faeces as they come into contact with the sheep's skin, but is also directed to the mite gut itself through ingested immunoglobulins. The resultant attachment of immunoglobulin to the mite gut inhibits nutrient absorption and ultimately egg production. Apart from affecting mite fertility and fecundity, immunoglobulins may also bind to the PM directly, stearically hindering the passage of molecules through it, thereby reducing the efficacy of utilization of ingested nutrients. It must not be forgotten though that the gut is a site of digestive proteolysis, so ingested antibodies and other effector molecules or cells may also be broken down before (or while) they act on their target (Eisemann and Binnington, 1994).

IgG levels can remain detectable (using contemporary ELISA techniques) long after the rapid growth phase, as mite faeces are still bound to the dried scab, and will continue to elicit an immune response as long as the scab is in contact with the skin. The duration of the response is related to the size of the lesion at the point of treatment. Antibodies can remain residual for 254 days for lesions of 4203 cm^2, 84 days for lesions of 252 cm^2 and 21 days for lesions of 130 cm^2 (Bates *et al.*, 2009). Thus, the exposure to specific *P. ovis* antigen does not stop with the end of parasite activity as *Psoroptes*

antigens can still be bound within the matrix of the lesion.

The phases of sheep scab appear to be significantly altered during reinfestation, presumably through acquired resistance. Bates (2000b) demonstrated that acquired resistance after a year was manifested by the lesion and mite burden remaining subclinical for over 50 days. Mite colonies eventually established and clinical sheep scab was observed, although the mite populations remained extremely low. Similar observations have been reported in *Psoroptes* spp. infestations of other hosts (Stromberg *et al.*, 1986; Guillot and Stromberg, 1987; Stromberg and Guillot, 1989; Urlir, 1991). Jayawardena *et al.* (1998) identified at least 22 proteins present in *P. ovis* extracts, with six recognized by mite-infested sheep serum. Pettit *et al.* (2000) detected ovine IgG in homogenates of *P. ovis*, and showed that immunoglobulins were (immuno-)localized to the surface of the cytoplasm of the gut cells. IgG in the mites' gut was partially digested as well as intact. The presence of intact IgG suggests that *P. ovis* may be susceptible to immunological control, like *B. microplus*.

This apparent acquired resistance to sheep scab may not be entirely immunologically modulated. Changes in the host skin character and increased age of the sheep may have also influence the pathology of reinfestation. Scab can have a significant effect on the quality of processed leather (Pearson, 1996), which suggests that there are significant changes in the character of the sheep's skin following *Psoroptes* infestation. These skin changes may also make it difficult for mites to feed following reinfestation.

Over the last 16 years a number of researchers around the world have investigated the possibility of a *Psoroptes* vaccine. The first documented investigations into the immunological control of sheep scab were by Stella *et al.* (1997), who compared the efficacy of total extracts (TE) and soluble extracts (SE) of homogenized *P. ovis* to protect against sheep scab. Significant differences ($P<0.01$) were observed between the untreated controls and the sheep receiving the SE fraction with respect to the extent of lesion growth. Although the TE-immunized sheep presented less severe symptoms, differences were not significant. In light of these results, it was therefore postulated that SEs of *P. ovis* may induce protection against sheep scab.

In 1992, a combined Veterinary Laboratories Agency (VLA) and Royal Veterinary College study also investigated a mite-derived vaccine against *P. ovis*. Groups of sheep were immunized with either: (i) soluble mite antigens (SA); (ii) membrane-bound antigens (MBA); or (iii) one of three fractions (F1, F2 and F3) of the soluble antigen, prepared by electrophoresis and continuous elution using BioRad PrepCell. Fractions F1, F2 and F3 contained low, middle or high molecular weight antigens, respectively. The immunized sheep (plus a non-immunized control group) were challenged with *P. ovis* and lesion areas and mite burdens monitored weekly for 7 weeks. The wide variation in parasitological values on individual sheep made statistical evaluation difficult. However, a consistent trend in the kinetics of lesion development was observed. An Efficacy Index (EI) was calculated in order to compare this trend for each antigen fraction. The EI was lowest for the non-immunized controls and highest for the animals vaccinated with the SA fraction; so the SA fraction, although not preventing infestation, appeared to modulate the pathology and severity of disease. Similarly, Pruett *et al.* (1998) found that a partially purified fraction of bovine *P. ovis* soluble proteins rendered eight out of 14 calves free from palpable lesions 8 weeks after challenge. A self-grooming behavioural response elicited by a pruritic immediate-type allergic reaction was also believed to be an effector.

Between 1997 and 2000, three combined studies were carried out between the VLA and the Moredun Research Institute (MRI), Scotland, to assess candidate *P. ovis* extracts as protective immunogens. The results of these investigations have been summarized by Bates (2000c) and Smith *et al.* (2002). Groups of yearling sheep were immunized parenterally with three

injections of immunogen (2 weeks apart), using QuilA as an adjuvant. They were challenged with *P. ovis* 1 week after the final injection. Control sheep were injected with the QuilA adjuvant only and similarly challenged. Protection against *P. ovis* was assessed by comparing the temporal progression of mite numbers and lesion areas in the immunized and control sheep.

Study One (carried out in 1997/8) compared two mite fractions ('ConA' and 'Wash Through'), each enriched for integral membrane proteins as vaccines, with an adjuvant (QuilA) only control. There were no significant differences with respect to lesion area between the 'ConA' and 'Wash Through' study groups compared with the QuilA controls. The 'Wash Through' fraction appeared to reduce mite numbers, but due to the extreme variability in mite numbers per individual sheep, these differences were not significant.

Study Two compared two different mite fractions (a soluble fraction, S2A; and a urea-extracted pellet, UEP) as vaccines with an adjuvant (QuilA) only control. There were no significant differences in lesion areas between the S2A fraction and the QuilA controls, while sheep immunized with the UEP fraction actually presented lesion areas greater than the QuilA control. However, mite numbers on sheep immunized with fraction S2A were dramatically reduced compared with the QuilA controls. Again, partly owing to the high variability between animals, no statistically significant differences were observed between the vaccinated and the control groups.

Study Three (1999/2000) investigated the soluble fraction S2A further, and also compared a new soluble fraction (S1) as a vaccine with an adjuvant (QuilA) only control. A number of sheep never developed lesion areas above 10.0 cm^2 throughout the 56 days of the study (three sheep in the S2A group, one sheep in the S1 group and four sheep in the QuilA controls). Data from these animals were removed from the study, and statistical analysis only applied to sheep presenting lesion areas above 10.0 cm^2. Statistical analysis (two-tailed, unequal variance, assumed) on log_{10}-transformed data (excluding the 'non-takers') revealed significant differences in lesion area and mite numbers between fraction S2A and the QuilA controls 42 and 56 days post-challenge ($P=0.0132$ and $P=0.0085$, respectively; and $P=0.0168$ and $P=0.0052$, respectively). There were also significant differences in lesion area and mite numbers between fraction S1 and the QuilA controls 42 and 56 days post-challenge ($P=0.1045$ and $P=0.0083$, respectively; and $P=0.0096$ and $P=0.0016$, respectively). There were no significant differences between the S2A and S1 fractions in either lesion area or mite numbers 42 and 56 days post-challenge ($P=0.1323$ and $P=0.1686$, respectively; and $P=0.5684$ and $P=0.6606$, respectively).

Another approach to scab vaccines may lie in thioredoxin peroxidase (TP), which is highly homologous with a secreted enzyme isolated from a tick, and has been found localized around the pharynx in *P. ovis* (McNair *et al.*, 2007). TP may be secreted by *P. ovis* and could react with the host immune system, thus making it a possible vaccine candidate.

Sarcoptes spp. vaccines

Studies have shown that goats can develop an acquired resistance to infestation by *S. scabiei* var. *caprae*. Vaccination against *Sarcoptes* in goats has been investigated, but to date has not been successful. No significant differences in lesion severity were observed between goats immunized with soluble *Sarcoptes* proteins compared with non-immunized controls. Immunization resulted in high levels of *Sarcoptes*-specific IgG, but failed to produce appreciable levels of IgE, as determined by ELISA. The lack of immune protection in vaccinated goats may be attributed to the absence of protective levels of IgE, as these appear to be important in immunity to *S. scabiei* infestation (Tarigan and Huntley, 2005).

Blowfly (*Lucilia sericata*) vaccines

Research into vaccination against fly strike can be aimed at either controlling the predisposing conditions (e.g. fleece rot caused by

Pseudomonas aeruginosa) or direct control of the fly larvae themselves (Sandeman, 1990).

The immunological control of the Australian sheep blowfly (*L. cuprina*) has been investigated by Bowles *et al.* (1996) and Tellam *et al.* (2000). Bowles *et al.* (1996) demonstrated that four larval antigens, from first-instar *L. cuprina*, are recognized in supernatants from cultures of antibody-secreting cells, and these have been successfully used to vaccinate sheep against larvae of *L. cuprina*. Significantly fewer strikes were recorded on vaccinated sheep than in controls, with surviving larvae from vaccinated sheep up to 85% smaller than larvae from unvaccinated sheep. Vaccinated sheep showed both humoral and cellular immune responses to the larval antigens (Bowles *et al.*, 1996). An isoelectric focusing fraction (pH 5.6–6.7) of homogenized first-instar *L. cuprina* larvae has been shown to contain a number of larval proteins that can inhibit the growth of *L. cuprina* larvae by a mean of 84% (±7%) in an *in vitro* feeding bioassay. In addition, the recovery of larvae after feeding on sera from sheep vaccinated with this fraction was significantly reduced (35% ± 13%). The anti-larval activity of these sera was shown to be mediated by ingested ovine antibodies (Tellam and Eisemann, 1998). Immunofluorescence and immunogold localizations showed that the immune response was directed at proteins from the larval PM, larval cuticle and, to a lesser extent, from basement membranes and microvilli of digestive epithelial cells (Tellam and Eisemann, 1998). Electron microscopic examination of larvae feeding on sera from sheep vaccinated with the isoelectric focusing fraction showed that the normally semipermeable PM was blocked on the luminal surface by an electron-lucent layer of undefined composition. This suggests that the electron-lucent layer prevents nutrients from moving from the gut to the underlying digestive epithelial cells, thereby starving the larvae (Tellam and Eisemann, 1998).

One possible anti-*L. cuprina* vaccine candidate is the intrinsic peritrophic matrix glycoprotein Peritrophin-95 which is found in the mid-gut of *L. cuprina*. Peritrophin-95 has been shown to be recognized by *L. cuprina* larvae in sera from infested sheep through immunoblots and ELISAs. This indicates that Peritrophin-95 stimulates the ovine immune system during larval infestation even though the protein is firmly attached to the peritrophic matrix in the larval mid-gut, and can therefore be considered as 'concealed' from the ovine immune surveillance system (Tellam *et al.*, 2000). However, soluble monomeric Peritrophin-95 has also been found in regurgitated or excreted material from larval *L. cuprina*, which indicates that Peritrophin-95, although suggested as a candidate *L. cuprina* vaccine antigen, is not a 'concealed' antigen as was previously thought (Tellam *et al.*, 2000).

High levels of serum antibody are produced by infested sheep against the excretory/secretory products of *L. cuprina*, although the response does not peak until there have been four successive infestations. Consecutive infestations of larger numbers of larvae induce a hypersensitivity response, which may affect survival of the first-instar (L_1) and second-instar (L_2) larvae. Antibodies are also produced against a range of components from all three instars of *L. cuprina* during experimental infestations, and sheep reinfested with *L. cuprina* show smaller wounds than those recorded for the primary challenge.

Two mechanisms of host resistance have been recognized: (i) the first occurs early in infestation, is probably associated with immediate hypersensitivity, and may control the initiation of protein (antibody) leakage; and (ii) the second occurs in later infestation and may result in the leakage of protein (antibody) that is capable of controlling larval survival.

Chewing louse (*Bovicola ovis*) vaccines

Investigations into the immunology of *B. ovis* infestations of sheep have been carried out in Australia (Eisemann *et al.*, 1994) and in New Zealand (Pfeffer *et al.*, 1994; Bany *et al.*, 1995a,b) as the first steps into a possible vaccine.

Biological Control

Pathogens of arthropods (viruses, bacteria, fungi, protozoa and nematodes) are widespread in nature and on occasions can decimate populations of their arthropod hosts. If these pathogens can be cultured in large numbers they may be used as 'biopesticides' and administered by methods similar to those used to apply conventional chemical ectoparasiticides.

Bacillus thuringiensis

The biological control agent *Bacillus thuringiensis* is becoming increasingly important in pest management, and accounts for 80–90% of all biological pest control agents ('biopesticides', or in this context, 'bio-ectoparasiticides') worldwide (Glare and O'Callaghan, 2000). *B. thuringiensis* is a Gram-positive soil bacterium, also found naturally on the skin of sheep and is, therefore, a possible 'eco-friendly' alternative to chemical ectoparasiticides.

B. thuringiensis produces insecticidal inclusion crystals (ICPs) (also known as δ-endotoxins) that are ingested by the target insect, usually in the larval stage (Schnepf *et al.*, 1998). In the insect mid-gut, the ICP/δ-endotoxin is solubilized by the alkaline pH of the gut, and the protein toxins (protoxin) are processed by the mid-gut proteases to release the active form (holotoxin). The holotoxin binds to specific cell surface receptors in the plasma membrane of the mid-gut epithelial cells, leading to formation of a lytic pore in the membrane which increases its permeability, and causes gut paralysis, cessation of feeding and eventually death (Knowles and Ellar, 1987). Two kinds of δ-endotoxin are produced: (i) cytolytic 'Cyt' proteins that are mostly specific to Diptera; and (ii) 'Cry' (crystal) proteins that have a wider range of specific target insects.

In comparison with most conventional ectoparasiticides *B. thuringiensis* formulations are purely biological products, harmless to humans and to most other non-target organisms (Meadows, 1993). They are also extremely safe for the environment and preparations containing *B. thuringiensis* are widely used in the forestry and horticultural industries (IPCS, 1999). Ectoparasiticide formulations are used to control the medically important dipteran species within the order Nematocera (mosquitoes and blackflies) (Mulla, 1990; Becker and Margalit, 1993; Ritchie, 1993; Becker, 1997). *B. thuringiensis* formulations leave no chemical residues in meat, milk or wool and have no expensive dip disposal costs. They are therefore ideally suited to organic producers.

Under laboratory conditions, strains of *B. thuringiensis* have been identified with activity against the chewing louse of sheep (*B. ovis*) (Pinnock, 1994) and the Australian sheep blowfly (*L. cuprina*) (Akhurst *et al.*, 1997; Gough, *et al.*, 2002; Heath *et al.*, 2004). *B. thuringiensis* applied to sheep fleece protected against blowfly strike for 6–11 weeks (Lyness *et al.*, 1994; Pinnock, 1994).

Studies by Drummond *et al.* (1995) demonstrated that the efficacy of *B. thuringiensis* against the sheep body louse (*B. ovis*) and SP (synthetic pyrethroid) toxicity to the louse appear to be inversely related. Furthermore, strains of *B. ovis* with an apparent monooxygenase-mediated pyrethroid resistance mechanism were more susceptible to *B. thuringiensis*. In addition, the SP susceptibility of both pyrethroid-susceptible and pyrethroid-resistant strains of *B. ovis* could be significantly reduced after administration of a monooxygenase inhibitor (e.g. piperonyl butoxide, PBO). Conversely, susceptibility to *B. thuringiensis* in a pyrethroid-susceptible strain of *B. ovis* was significantly enhanced after administration of a monooxygenase inducer (sodium phenobarbital) (Drummond *et al.*, 1995).

To date though, no commercial preparation of *B. thuringiensis* has been released for the control of insect pests of livestock. One of the limiting factors has been the availability of specific strains with high toxicity to insect pests of sheep and cattle (Gough *et al.*, 2002).

Entomopathogenic fungi

Entomopathogenic fungi are natural components of soil flora worldwide and can be a

cause of fungal diseases of insects. Two species of fungus, *Beauveria bassiana* and *Metarhizium anisopliae*, have been investigated as potential biocontrol agents against sheep and goat ectoparasites.

Psoroptes ovis

Smith *et al.* (2000b) demonstrated that *M. anisopliae* had a high level of pathogenicity to *P. ovis*. Three days after exposure to fungal conidia, all mites were dead, and 6 days after exposure dead mites had fungal hyphae protruding from their cuticular surfaces. Passaging the fungus either once or twice through the host had no significant effect on its subsequent infectivity (Smith *et al.*, 2000b). High-temperature-adapted isolates of *M. anisopliae* formulated in silicone oil have also been shown to be good candidates as control agents under the conditions found at the sheep skin surface.

In vitro laboratory studies have shown that *B. bassiana* can sporulate on the body surface of *P. ovis* and infect healthy mites coming into contact with the infected cadavers (Lekimme *et al.*, 2006). Oviposition by *P. ovis* was not reduced by infection with *B. bassiana*, but both the hatchability of the eggs and the lifespan of the emerging larvae were significantly reduced (Lekimme *et al.*, 2006). *In vivo* studies in which dry conidia were applied to scab-infested sheep have demonstrated that *B. bassiana* infected greater numbers of *P. ovis* than *M. anisopliae* (Abolins *et al.*, 2007).

Entomopathogenic nematodes

The entomopathogenic nematode *Heterotylenchus autumnalis* has been shown to be highly effective in reducing numbers of the face fly (*Musca autumnalis*) of cattle (Harewood and James, 1980). Six other entomopathogenic nematode species, *Heterorhabditis bacteriophora*, *Steinernema intermedia*, *Steinernema glasseri*, *Steinernema anomali*, *Steinernema riobrave* and *Steinernema feltiae*, all obligate parasites of insects, have been investigated for their efficacy against *L. sericata* (Tóth *et al.*, 2005). However, they appear to be only active at temperatures below 37°C, and were not therefore suitable for administration directly to sheep for the control of blowfly strike.

Trapping

Sheep blowflies (*Lucilia* spp.) travel only relatively short distances (up to 4 km) during their lifetime, mainly searching for sources of protein (essential for egg development) or an egg-laying site (usually a susceptible sheep). Thus it is possible to reduce blowfly populations over a trapped area using an efficient trapping system.

Bait-bin traps

As early as the 1930s, offal and sodium sulfide-baited traps were shown to attract and catch large numbers of blowflies in Australia, and when used intensively were capable of reducing fly strike (Levot, 2009b). In the 1990s, interest was once again focused on large offal-baited traps, which were constructed out of 200 l proprietary plastic rubbish bins or metal drums. These bait-bins did not reduce fly strike in sheep, but users were impressed by the sheer volume of flies that could be captured. However, they were sometimes mistaken in their belief that all green blowflies were the Australian sheep blowfly (*L. cuprina*) (Levot, 2009b).

To be efficient, bait must be attractive to blowflies and be located in the vicinity of blowflies, and thus move with the sheep. Most blowflies have evolved to breed in carrion where there is intense competition between fly species for sufficient food. Some species have adapted to this competition by only breeding in fresh carcasses; these are 'primary' blowflies. Other 'secondary' species, such as *Chrysomya rufifacies*, are attracted to already flyblown carcasses and have larvae that display aggressive behaviour towards primary species, driving them from the carcass. As a consequence, an offal-baited trap will initially attract primary species and then become

attractive to 'non-target' secondary species (Levot, 2009b). To prevent this, bait-bins now incorporate mesh-covered entrance slots that allow *Lucilia* to enter but prevent the entrance of the larger *Chrysomya* or *Calliphora* species.

An effective design for a bait-bin has been described by Levot (2009b). Large UV-stabilized plastic rubbish bins with wheels are the most suitable and easily transported. Wire mesh (with holes measuring 3.3–4.0mm) -covered entrance slots are cut out high on two sides of the bin. Bins should be painted yellow for optimal attractiveness to blowflies and well anchored to prevent being blown over, knocked over or washed away. For bait, a whole sheep carcass or part of a carcass is used. One litre of a 20% sodium sulfide solution is poured over the carcass to produce an instant stench that will pervade over several hundred metres. The lid must be shut and a catch installed to prevent interference. A registered ectoparasiticide is sprayed on the inside of the bait-bin and over the bait to actively kill blowflies. The number of bait-bins required will vary with individual circumstances. Two to three bins may be needed on a property running 1500 sheep (Levot, 2009b).

Bait-bins must be used at the correct time and regularly maintained. They should be deployed in anticipation of blowfly activity (late winter/early spring) and be located near sheep or areas frequented by sheep (Levot, 2009b). While in use, the service interval for the bait-bins will depend on temperature, abundance of flies, humidity, trap location, residual life of the ectoparasiticide spray, etc. Poorly maintained bait bins will be inefficient and a nuisance (Levot, 2009b).

The LuciTrap

The Australian sheep blowfly, *L. cuprina*, has adapted to breeding on sheep to avoid competition with other species. Although still attracted to the putrefactive odours emitted from decaying carcasses, *L. cuprina* responds strongly to sheep odours, particularly those associated with fleece rot infection. Consequently, offal/carcass-baited traps are not ideal (Levot, 2009b). Attractant mixtures based on 2-mercaptoethanol, indole, butanoic/pentanoic acids and a sodium sulfide solution gave 5- to 20-fold higher *L. cuprina* catches than a liver standard. These synthetic attractants were effective and selective for *L. cuprina* and could be packaged in controlled-release dispensers to generate constant, prolonged release of the attractant.

The LuciTrap sheep blowfly trapping system was developed by the Queensland Department of Primary Industries and Fisheries in conjunction with University of Queensland and Bioglobal Pty Ltd. The LuciTrap system consists of a specifically designed translucent bucket made from tough UV-stabilized plastic, with a removable lid with a flat surface, entrance cones that allow the blowflies to enter but not to leave the trap, and holes for fixing to a tree or fence post at sheep height above ground. A yellow lid is fixed to the bucket with a twist and lock design (Knights *et al.*, 2008). Brackets are built in to the lid to hold bottles of chemical attractant containing a patented blend of three chemicals (LuciLures A, B and C) that mimic the odours of fleece rot, animal carcasses, urine and faeces. Wicks at the top of each bottle regulate the release rate of each attractant and once the bottles are uncapped the attractant evaporates into the air for up to 6 months (Knights *et al.*, 2008).

Manufacturers recommend the use of one trap per 100 sheep. LuciTraps need to be located close to watering points, along bore drains and creeks and at other regular sheep camps. This will take advantage of the fact that adult flies need access to water to survive and that most newly hatched flies emerge near sheep camps (Wilson and Armstrong, 2005). Any traps not catching blowflies should be moved to better locations. Trapping over a wide area is optimal and may require the cooperation of neighbouring properties. Using LuciTraps to trap blowflies can substantially reduce fly strike, particularly if carried out by several neighbouring properties (Wilson and Armstrong, 2005).

The cost-effectiveness of trapping should be carefully considered. Research has demonstrated that except for times when blowfly numbers are extraordinarily low (e.g. during periods of prolonged drought) very few blowflies need to be present before fly strike occurs on 'susceptible' sheep. It is the presence of susceptible sheep rather than blowfly numbers that drive blowfly strike. However, the more blowflies are present when there are susceptible sheep, the greater the risk. Trapping in the cooler months when blowfly numbers are low can slow down the rate of population increase when conditions are favourable (Wilson and Armstrong, 2005). It may also prevent strikes being established in circumstances where favourable conditions are short lived and blowflies are unable to breed in sufficient numbers in the time available (Wilson and Armstrong, 2005). Trapping can also provide an early warning of a build-up in blowfly numbers and allow appropriate control strategies to be implemented (Wilson and Armstrong, 2005), so the LuciTrap offers a most effective early warning for the presence of *L. cuprina* (Levot, 2009b). Setting out LuciTraps in the late (Australian) winter and regularly checking the traps is an efficient way of finding when the overwintering blowfly population first emerges and, as such, is a useful tool in an integrated fly strike control programme. However, in times of high blowfly risk, trapping alone will not provide adequate protection against strike (Levot, 2009b). Studies using the LuciTrap in South Africa have also shown it to be a vital component of an integrated pest control programme.

LuciTraps should be maintained in working order throughout the expected fly season. The three attractant bottles must be replaced at the same time, when the first bottle runs low (10–20% left). The attractant loses its effectiveness at this stage, even though there may still be a strong odour (Knights *et al.*, 2008). In addition, the trap bucket must remain translucent to maintain it effectiveness and therefore needs to be cleaned regularly.

Traps developed in the UK

A trap designed by University of Bristol in the UK has been investigated for use in the control of the European blowfly, *L. sericata*. The trap is constructed from 4 mm thick, white, corrugated plastic, folded to form an inverted, three-sided, hollow pyramid. Each side is 25 cm in length. To allow flies to enter (and prevent larger insects such as butterflies and dragonflies from entering) sections of each of the three sides of the pyramid are cut away to produce four slits: 16, 12, 9 and 5 cm in width from top to bottom of the inverted pyramid; each slit is 2 cm high. In the lid of the trap an 8 cm long, oval slit is cut out to allow an oblong black sticky trap (7 × 24.5 cm) to be inserted so that most of the strip rests within the trap, leaving a 4 cm section protruding from the top. All traps are baited with 10 g freeze-dried liver placed into a 100 ml plastic bait pot, fastened by a cable tie inside the trap (Broughton and Wall, 2006). The incidence of strike was on average five times lower on farms where trapping was carried out, either with or without additional chemical prevention. However, the reduction in the number of strikes was not statistically significant between trapping only and the use of additional chemical prevention (Broughton and Wall, 2006).

Odour-baited triflumuron-impregnated traps have been assessed for efficacy against *L. sericata* in England (Smith and Wall, 1998). Traps were constructed from 41 × 41 cm squares of aluminium sheet, covered by white cloth dipped in a mixture of sucrose solution (50% w/v) and triflumuron (10% suspension concentrate). Each trap was baited with 300 g of liver and 10% sodium sulfide solution (Smith and Wall, 1998). Under field conditions the density of *L. sericata* was reduced to zero and remained significantly low throughout the period during which the traps remained in the field (Smith and Wall, 1998).

Sterile Insect Release

The Sterile Insect Release Technique (SIT) has been used against New World

screw-worm species in the USA and Central America, exploiting the fact that the fly only mates once. SIT involves saturating the environment with artificially reared sterile male flies, resulting in the majority of wild females mating with sterile males and producing sterile eggs. This can dramatically reduce screw-worm populations and, if maintained over several generations, can achieve eradication.

Similar systems have been developed to render populations of *L. sericata* infertile by the release of 'treated males' into the wild. Male *L. sericata* have been sterilized with gamma radiation and released into the wild to compete with the native population. Trials conducted on the island of Lindisfarne, off the north-east coast of England, showed no reduction in the population density of the native *L. sericata*. Failure was probably due to inadequate sterilization or irradiated males unable to compete with native flies. Apholate has also been used to chemically sterilize male *L. sericata*. This compound leaves sperm competitive with untreated males, and female flies will readily mate with treated males, but are rendered permanently infertile. The sperm remains alive and motile and capable of penetrating the ova but the zygote produced is unable to develop. Treated flies can be released but apholate can also be applied as a bait. Released flies are specific for their own species and the technique is ecologically sound.

Selective Breeding

In Australia, breeding programmes are directed towards the development of sheep that require less care by having short tails and the natural ability to moult breech wool. The recent identification of a merino line that has a bare crutch would seem to be the ideal sheep for the system. Most of the traits associated with wool production have a medium to high heritability, and selection programmes to improve quantity and quality continue. Breeding plain breech merinos would minimize breech wrinkle and provide a permanent solution to managing breech strike that is cost effective.

In merino lines that are not specially bred as described above, it is important when selecting rams for breeding to consider their susceptibility to fly strike. It may be unwise to purchase stock from flocks where the prevalence of breech strike is high. In selecting fly-strike-resistant rams, rams with excessive body wrinkle should be avoided, particularly those with tight wrinkles around the neck and crutch. Rams producing bright white to slightly cream coloured fleece that is soft handling (high wax to low suint ratio) appear to be less susceptible to fleece rot compared with those with yellowish harsh handling (low wax to high suint ratio) fleece.

It should also be possible to achieve other advances in in ectoparasite resistance by selective breeding.

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Economic Damage

Ectoparasites are a major concern to the sheep and goat farmer and are a significant drain on resources (Heath, 1994). Also, the presence of animals that are not healthy within a flock clearly has welfare implications for those animals and their companions. Sheep infested with sheep scab mites (*Psoroptes ovis*) or with myiasis may suffer immensely if they remain untreated. Ectoparasites can therefore seriously compromise the welfare of flocks/herds and individual animals. All sheep/goat owners/keepers in the UK are advised to be aware of the *Code of Recommendations for the Welfare of Livestock* for sheep (Defra, 2003) and for goats (Defra, 1989), which emphasize the importance of preventing and treating for ectoparasites. Effective chemical treatments are available for prevention and control, so flock/herd owners could face prosecution in the UK for animal cruelty if they neglect to prevent or treat for ectoparasites within their flocks/herds.

The continued application of ectoparasiticides, the labour associated with preventing or alleviating ectoparasite damage, and the production losses or deaths that cannot be prevented can result in a net loss to farming due to ectoparasites that cannot be denied (Heath, 1994). Estimates of the monetary losses due to ectoparasites can be computed, but their long-term value is doubtful – particularly when seen against a background of fluctuating world prices and occasional reversals of differential values between carcasses and by-products (Heath, 1994).

Decreased production and treatment costs of blowfly strike in New Zealand and Australia were reported to be in excess of NZ$30 million and AU$161 million in 1994 and 1995, respectively (Heath, 1994; McLeod, 1995). The cost of chewing lice (*Bovicola ovis*) to the Australian sheep industry has been estimated to be between AU$169 and 350 million annually (McLeod, 1995; PIRSA, 2011). In New South Wales alone, *B. ovis* infestations cost AU$148 million in treatment and lost production. The total cost of ectoparasites to the Australian sheep industry in losses in wool quality and quantity, sheep deaths, and expenditure on ectoparasiticides and labour has been estimated to be AU$280 million annually (Knight *et al.*, 2008).

Drummond *et al.* (1981) estimated losses from mange mites on livestock production in the USA to be US$14.4 million. Sheep scab (*P. ovis*) can have profound effects on the health, welfare and economics of infested flocks. In 1989, psoroptic mange was considered the most damaging ectoparasite affecting Argentinean sheep flocks, with estimated annual losses

calculated to be US$150 million (Nuñez, 1989). In 1997, *P. ovis* was calculated to cost the UK sheep industry £3–4 million a year in lost income. Eight years later, the cost (with respect to lost performance, preventive measures and treatment of affected animals) was calculated to be £8 million annually. Most of these costs were for preventive measures, therefore, short of eradication, a reduction in incidence will have a limited effect on costs (Nieuwhof and Bishop, 2005). Sheep scab (and to a degree all ectoparasites) can have a wide range of effects on production, including:

- ewe and lamb mortality;
- loss in body condition;
- secondary infections (particularly through rubbing and scratching);
- hypothermia;
- low birth weights;
- reduced milk yield and lamb growth rates;
- reduced wool, pelt and leather values;
- cost of treatment (products, labour and/or hire of contractor);
- losses due to meat, milk and fleece withdrawal periods; and
- repair of fences and buildings – damage through excessive rubbing and scratching.

Stubbings (2007) investigated the financial losses caused by sheep scab within a hypothetical lowland flock in the UK and calculated a 25% increase in lamb mortality, an increased lamb finishing time of 2 weeks (owing to poorer milk yields and poorer growth rates), additional lamb feed (creep) for the extra 2 weeks, additional ewe feed due to reduced body condition at lambing, cost of treatment (a single injection of doramectin) and reduced fleece value of 50%. Overall, within the scab-infested flock a potential profit of £5.27 per ewe was reduced by £18.84 to a loss of £13.57 per ewe.

As can be seen from the above example, the costs associated with ectoparasites can be broadly divided into those associated with production losses (fatalities and other losses directly associated with livestock production, and reduced meat, milk, fibre or leather yields, as well as effects on the sale of stock) and those associated with treatment. Treatment itself can be divided into the costs of cure and the costs of prevention.

Production Losses

Fatalities

If left untreated, ectoparasite infestations (particularly blowfly strike or sheep scab) can be fatal. Such fatalities are not only unacceptable and preventable; they also result in a loss of income through lost breeding stock or meat and/or wool production, and may incur extra expense for the legal disposal of the carcass. In the UK, all fallen stock most be disposed of by incineration by a licenced operator; this adds the costs of transport and incineration (usually at a fixed rate per kilogram dead weight) to the overall costs of fatalities. Failure to dispose of fallen stock in the correct manner may lead to prosecution and, if found guilty, payment of a fine and court costs.

Death in sheep infested with *P. ovis* may occur through debility and exhaustion (Downing, 1936), dehydration (a direct result of the feeding of large numbers of mites) (Roberts *et al.*, 1971), secondary bacterial infections (e.g. pneumonia or septicaemia through self-inflicted wounds) (Roberts *et al.*, 1971) or hypothermia. Infested sheep also have lowered resistance to other infections and parasites (e.g. parasitic gastroenteritis – PGE, and *Pasteurella*). Epileptiform fits can cause death through internal haemorrhage (Downing, 1936; Bygrave *et al.*, 1993). In goats, adverse effects of severe infestations of the African goat louse (*Linognathus africanus*) can include anaemia and death, especially in kids (Durden and Lloyd, 2009).

Two opinions exist concerning the economic effects of nasal bot fly (*Oestrus ovis*) larvae on sheep/goat production. Buchanan *et al.* (1969) demonstrated no significant difference between the condition of affected and unaffected sheep. In the USA, Jensen and Swift (1982) reported that morbidity may be high in a flock but mortality nil, and in Australia, Brightling (1988) reported that little or no production loss is observed, with

oestrosis rarely being recognized as a serious problem. In Britain, severe cases of oestrosis can constitute a serious welfare issue, but are not incriminated in significant production losses. However, in the former USSR and central Asia, *O. ovis* is considered to be a serious problem, with vast treatment programmes instigated. Grunin (1957) reported that in dry years in the former USSR, heavy infestations were responsible for high mortality, and Antipin *et al.* (1959) stated that severe infestations of *O. ovis* (60–80 larvae) could produce considerable mortality.

Ram fertility

Thickening of the skin as a result of *Chorioptes* infestation can affect scrotal temperature regulation, and in extreme cases, lead to testicular atrophy and reduced fertility (Rhodes, 1976). The latter condition is apparently reversible, as sperm production and fertility are re-established after treatment (Urquhart *et al.*, 1987). Live sheep scab mite (*P. ovis*) have been observed on the scrotum of rams (Spence, 1949), and are presumably capable of causing similar infertility problems.

The presence of active ectoparasites can have effects on reproductive performance. Irritation and discomfort caused by sheep chewing lice (*B. ovis*) can result in reduced libido and reduced testicular weights.

Apart from the high cost of replacing rams that die, any level of fly strike will have a damaging effect on fertility due to an increase in body temperature and its subsequent effect on sperm production, though the size of the strike lesion is not a good indicator of the effect it will have on sperm production. Rams that are fly struck will also be less interested in serving ewes. In addition, if they have body or breech strike their offspring may be prone to fly strike and should be culled.

Conception

Conception rates can be profoundly affected by ectoparasites, particularly if a ewe's body condition is low because of an infestation. Further, ewes presenting with active scab (*P. ovis*) lesions on the back (particularly towards the rump) may infest rams on the belly and crutch during mating – and rams presenting with lesions at these sites may be unwilling to mount ewes or remain for only a short period of time. Rams infested at these sites may also transfer mites to the backs of ewes and the ewes, in turn, may not accept the ram. Conception rates may therefore be low. Losses at conception may also occur through the treatment aimed at controlling ectoparasites, as there is the possibility that the excessive stress caused by the treatment of sheep infested with *P. ovis* or other ectoparasites (particularly by plunge dipping) within the first month of gestation may cause unattached ova to float out of the ewe (Dymond, 1984).

Gestation

Ectoparasite infestations during pregnancy could affect the development of the growing fetus. The ewe or nanny may be too preoccupied with rubbing and scratching to ingest or metabolize sufficient nutrient, and nutritional stress in the second month of pregnancy can lead to fetal reabsorption (Dymond, 1984) and possibly also to pregnancy toxaemia (twin lamb disease).

Reduced lamb/kid crops

Lambs born to mothers with moderate-to-extensive sheep scab (*P. ovis*) infestations may be stillborn or born weak. In the UK, like other fallen stock, stillborn lambs also incur the costs of incineration.

Effects on lamb/kid live weight gain

Ectoparasites can have a negative effect on the growth of lambs or kids. Sargison *et al.* (1995b) observed that lambs born to scab mite (*P. ovis*) infested mothers were 10% lighter at birth, and milk production may

also be affected, thus affecting early lamb development. Newborn lambs can be infested with *P. ovis* from their mothers (vertical transmission) or from other infested ewes in the lambing shed (horizontal transmission). Lambs below 1 month old tend not to present clinical sheep scab, although mites maybe present on the skin (Bates, unpublished observations).

Clinical symptoms of scab develop as the lamb grows, and a 30% loss in weight gain has been recorded in growing lambs (Kirkwood, 1980). Calves severely infested with psoroptic mange (*P. ovis*) have a significantly lower daily gain-to-feed ratio and energy retention compared with control calves, which increases their maintenance energy requirements by over 50%. For each 10% increase in body surface affected by *P. ovis*, the maintenance energy requirement for infested calves increased by 0.5 Mcal/day (Cole and Guillot, 1987); this kind of figure may also apply to growing lambs infested with *P. ovis*.

Feed consumption has been shown to be significantly lower in sheep with active, progressing sheep scab (Rehbein *et al.*, 2000a). Lambs prophylactically treated with ivermectin (administered as a constant release capsule, CRC) demonstrated a weight gain of 20.9 kg after 126 days, whereas untreated control sheep with an actively progressing infestation of *P. ovis* demonstrated a reduced weight gain of only 12.8 kg over the same time period (Rehbein *et al.*, 2000a) (Table 11.1).

Appropriate treatment can eradicate *P. ovis*, and the lamb can then resume normal growth. For example, plunge dipping in diazinon dipwash can resolve the condition, and lambs can thereafter increase in weight (Kirkwood, 1980), although this weight gain may be delayed and it is unlikely that the lambs will reach market weight as quickly as uninfested lambs of the same age, even after the expense of extra feeding. The lost market potential may also result in holding and feeding lambs for extended periods until the next marketing opportunity arises, together with the expenses associated with this.

Lambs with active infestations of *P. ovis* that received an ivermectin CRC 84 days after *P. ovis* challenge (a point at which weight gain was similar to that of untreated controls) were cured of disease and, at the end of the study, had gained 2.1 kg more than the untreated controls but 6.0 kg less than the lambs receiving a prophylactic treatment (Rehbein *et al*, 2000a) (Table 11.1). Similar results were observed by O'Brien *et al.* (1999), when greater mean weight gains were seen after the administration of an ivermectin controlled release (CR) bolus.

The effects of chewing lice (*B. ovis*) infestations on live weight gain in sheep are equivocal. Controlled studies in New Zealand and Australia failed to show any adverse effects (Kettle and Lukies, 1982; Niven and Pritchard, 1985). No significant differences in lamb percentages and lamb weights at weaning between *B. ovis*-infested and *B. ovis*-free sheep were observed over a 4 year period, and *B. ovis* had no effect on lambing percentage or lamb growth rate (Kettle and Lukies, 1982).

Table 11.1. Weight gain seen in lambs infested with *Psoroptes ovis* (sheep scab mites) following prophylactic or curative administration of an ivermectin constant release capsule (CRC) (after Rehbein *et al.*, 2000a).

	Weight gain (kg)		
Time post-treatment (days)	Untreated	Prophylactic (administered day 0)	Curative (administered day 84)
0–84	9.6	13.9[a]	8.4
0–126	12.8	20.9[a]	14.9

[a] Significantly different ($P < 0.05$).

However, studies in the UK have demonstrated a mean 18% live weight gain in treated compared with untreated sheep (Ormerod and Henderson, 1986). Sheep with low weight gains due to poor nutrition or other stress may be more susceptible to lice and develop heavier infestations (James *et al.*, 1998). Thus, it is often assumed that observed heavy infestations of lice are the cause of weight loss and/or loss of body condition. As for *B. ovis* in sheep, infestations of the chewing louse *Bovicola limbata* do not affect the body weights of infested angora goats (Brown *et al.*, 2005). Similarly, no significant differences in body weight gain have been observed between sheep infested with keds (*Melophagus ovinus*) compared with treated ked-infested sheep (Olaechea *et al.*, 2007b).

Antipin *et al.* (1959) stated that infestation by nasal bot fly (*O. ovis*) larvae could be responsible for a reduced weight gain, and Illchmann *et al.* (1986) reported weight losses ranging from 1.1 to 4.6 kg per infested sheep. Infestations by goat warble (*Przhevalskiana silenus*) larvae can result in a significant and positively correlated ($r=0.89$) decrease in body weight of 2.6 ± 1.3 kg per goat over 133 days (Liakos, 1986).

Effects on carcass conformation

Carcasses of *P. ovis* infested lambs have been shown to have significantly lower ($P<0.05$) warm and cold weights, carcass yield, rib-eye area, back-fat thickness, muscle scores and lower muscle pH 1 h after slaughter (Rehbein *et al.*, 2000a). In contrast, no significant differences were observed in these markers in sheep treated (with an ivermectin CRC) 84 days into infestation (Rehbein *et al.*, 2000a).

Milk and milk products

Ectoparasites can affect milk yield, either directly, through their effects on the host or indirectly through the use of ectoparasiticides. Direct losses of up to 10% in milk yield have been reported from *O. ovis* infestations (Illchmann *et al.*, 1986). Ectoparasite infestations of sheep or goats producing milk for human consumption are problematic, particularly in relation to the specified milk withdrawal periods associated with ectoparasiticide treatments. Infested animals have to be treated for welfare reasons, but in the UK there are no ectoparasiticides licenced for use on milking sheep or goats. Thus, milk has to be destroyed, with an associated loss of income.

Fibre

Losses in fibre production can be through the actual loss of wool/fibre, either from localized areas or from the majority of the body. Attached wool may be of poorer quality, matted as a result of dried exudates and contain unacceptably high levels of undesirable foreign matter as a result of infestation (blood, exudates, dead parasites, parasite exuvia (skins) and faeces) or excessive rubbing and scratching (dirt, hay, straw and other vegetable matter). Wool can be devalued through penalty payments incurred as a consequence of matted fleece and impregnation with foreign material.

Fleece losses due to scab mites (*P. ovis*) can occur through destroyed wool follicles, rubbing off, or lifting away with rising scab. Losses of 0.2 kg of fleece per animal have been calculated (Kirkwood, 1980). Deterioration in the tear properties of the wool and the carding index have been recorded for *P. ovis* infested fleeces, and these downgrade wool values (Olaechea *et al.*, 1997). Also, wool regrowth can differ from normal wool in texture and pigmentation. In the Herdwick breed, for example, regrowth is grey/brown, in downland sheep it is sooty brown or black and in Welsh mountain sheep it is bright orange/tan.

Lambs receiving a prophylactic administration of an ivermectin CRC had significantly ($P<0.05$) greater clean fleece weight (1.5 kg) and fleece yield (52.1%) than untreated controls (0.9 kg and 34.1%, respectively) or lambs with active scab infestations treated on day 84 (1.0 kg and

47.8%, respectively) (Rehbein *et al.*, 2000b). Clean fleece weight and fleece yield were significantly greater ($P=0.055$ and $P<0.001$) for lambs treated on day 84 than untreated controls (Rehbein *et al.*, 2000b).

The economic significance of chewing lice (*B. ovis*) in wool-producing flocks is dependent on the system used to determine the price paid, and the price differentials applied to lower grades of wool (Kettle, 1985). The economic significance of *B. ovis*, therefore, depends on their effects on grading, which directly affects prices. Wool grading is based on many parameters, including: (i) fibre diameter, length and strength; (ii) colour and brightness; (iii) bulking capacity; (iv) presence or absence of staining or cotting (matting, tangling); and (v) the amount of extraneous vegetable or mineral matter (Kettle, 1985). All of these can be affected by louse infestation, and irritation by sheep keds (*M. ovinus*) can mechanically damage the fleece (Olaechea *et al.*, 2007b).

Irritation by *B. ovis* causes sheep to bite and rub the infested area in an effort to alleviate discomfort. This biting and rubbing can cause fleece derangement, resulting in reduced fibre strength which, in turn, reduces the yield of clean wool, the quality of the fleece and the processing quality of the wool, without affecting the fibre diameter or live weight (Lipson and Bacon-Hall, 1976; Kettle and Lukies, 1982; Wilkinson *et al.*, 1982; Niven and Pritchard, 1985; Joshua, 2001). However, Cleland *et al.* (1989) found no significant effect on fibre length, although Wilkinson *et al.* (1982) found that the mean length of the top wool was reduced on louse-infested sheep.

Lousy sheep can cut about 10% less wool (Joshua, 2001). However, the degree of damage due to *B. ovis* is related to the severity of the infestation. Irritation caused by modest infestations is enough to cause scratching and rubbing, resulting in damage to fleece. Light infestations have less impact. Niven and Pritchard (1985) recorded a 74% yield for light lice infestations, 72% for medium infestations and 68% for heavy infestations. Sheep with low louse numbers produced significantly more sound fleece and less cast wool than moderately or heavily infested sheep. Overall, *B. ovis* infestations can record a reduction in wool value per sheep of up to 30% (Niven and Pritchard, 1985). In a study investigating artificial *B. ovis* infestations over a 3 year period, reductions in fleece value of up to 31% and 38% were recorded in years two and three, respectively; notably, no measurable losses were recorded in the first year (Elliot *et al.*, 1986; Cleland *et al.*, 1989). The economic effects of *B. ovis* are more pronounced in the merino breed, with Australian merinos showing significant reductions in greasy and scoured fleece weights and scoured yield, and significant increases in carding losses compared with Romney crosses (Kettle, 1985). Greasy and clean fleece weights from treated sheep were significantly higher than those of untreated controls (Niven and Pritchard, 1985). Reduced weights of greasy wool between 0.2 and 0.9 kg and of clean wool between 0.2 and 1.1 kg per sheep have been recorded, depending on the level of infestation (Wilkinson *et al.*, 1982; Niven and Pritchard, 1985: Elliot *et al.*, 1986; Cleland *et al.*,1989; Joshua, 2001).

Sheep treated repeatedly with cypermethrin produced significantly more sound fleece wool and less cast fleece wool than untreated controls, with differences in wool value between treated sheep and controls ranging between AU$0.45 and AU$3.19 per sheep (Niven and Pritchard, 1985). Similarly, studies in the north-east of England demonstrated that infested sheep treated with a propetamphos pour-on produced 34% more wool than untreated controls, and the wool from the treated sheep was of better quality (Ormerod and Henderson, 1986).

Kettle and Lukies (1982) objectively measured colour (yellowness and brightness) in seven trials using a refractance colorimeter and demonstrated that louse-infested wool was more yellow and less bright than wool from uninfested sheep. Colorimetric comparisons of core samples from lousy sheep were significantly less bright and, in most cases, more yellow in colour; both these features lower wool quality (Kettle, 1985). Wool staining by *B. ovis* irritation increases suint and skin secretions, which discolour the fleece.

The effects of *B. ovis* infestation on the processing qualities of wool are shown in Table 11.2. *B. ovis* can reduce top wool yield and mean fibre length of the top, and increase carding losses and noil (short broken fibres removed during combing of the carded wool into top wool). However, *B. ovis* does not affect fibre diameter of the top wool or the number of neps (knotted fibres). Cotted wool is worth about 10% less than uncotted wool (Joshua, 2001).

In Australia, the annual costs/losses to wool growers through *B. ovis* infestation have been estimated to be above AU$160 million (McLeod, 1985). Production losses can range between AU$9.6 and 12.1 per sheep for fine (18μm) wool and AU$ 6.4 and 7.4 per sheep for strong (24μm) wool (Wilkinson *et al.*, 1982). It costs time and labour to muster and treat sheep: approximately AU$2 per sheep/year accounts for fixed and variable costs (Joshua, 2001).

Infestations of the sheep ked (*M. ovinus*) can also result in differences in the percentage yield of scoured wool and in fleece colour, and excreta can stain the wool and downgrade the fleece (Olaechea *et al.*, 2007b).

In angora goats, infestations of chewing lice (*B. limbata*) can adversely affect both the quality and quantity of the mohair produced (Brown *et al.*, 2005), and *L. africanus* can cause fleece damage in goats (Durden and Mullen, 2009).

Antipin *et al.* (1959) stated that infestations of nasal bot fly (*O. ovis*) larvae could be a source of reduced wool quality, and in the former USSR and central Asia, oestrosis has been reported to result in wool losses ranging from 200 to 500g per sheep (Ilchmann *et al.*, 1986).

Leather

Compulsory dipping for the control of sheep scab in Britain between 1974 and 1992 not only reduced the prevalence of scab but also controlled other sheep ectoparasites with a potential to downgrade leather quality (e.g. blowflies, chewing lice (*B. ovis*) and keds (*M. ovinus*)). With the relaxation in compulsory treatment in 1989, tanners and fellmongers saw an increase in parasite damage and a decline in sheep skin (pelt) quality. Between 1989 and the deregulation of scab as a notifiable disease in 1992, the total number of pelts damaged by all sheep ectoparasites had increased approximately fivefold. The proportion of skins affected with a specific type of scarring associated with sheep scab increased from 1–2% in 1989 to 15% in 1995 (over 25% at the worst time of year) (Pearson, 1996). Damage due to keds (*M. ovinus*), rarely seen in the UK between 1975 and 1988, was recorded as 0.5%. The incidence of the skin defect known as 'rash', associated with chewing lice (*B. ovis*) and mycotic dermatitis (*Dermatophilus congolensis*), had also increased from 1–2% in 1989 to 5–6% in 1995. Lower quality skins caused by ovine ectoparasitic infestations (lice, scab and blowfly myiasis) can only be used to produce lower grades of leather, which command reduced prices, and a potential loss in leather returns of £15–20 million, or £1.0 per lamb (Pearson, 1996; British Leather

Table 11.2. Effect of chewing louse (*Bovicola ovis*) infestations on wool processing performance (Source: Wilkinson *et al.*, 1982).

	Level of infestation				
Wool processing characteristic	No lice	Very light	Light	Medium	Heavy
Scouring yield (%)	66.8	68.6	63.0	62.0	62.6
Card loss (%)	9.8	10.9	12.3	12.4	13.3
Noil (%)	4.1	3.4	4.8	5.2	5.4
Top and noil yield (%)	60.5	61.4	55.7	53.7	53.3
Mean length of top wool	8.3	7.4	7.7	7.7	7.2

Confederation, personal communication). Although this money may not be reflected directly in what farmers receive for their animals, over a period of time the reduced value of the skin has to be passed back up the chain (Pearson, 1996). Damage to skins by flea (*Ctenocephalides* spp.) infestations has also been recorded to cause considerable losses to the leather industry, particularly in Nigeria, Kenya and Tanzania (Kusiluka and Kambarage, 1996).

Damage to sheep or goat pelts can occur through three separate routes:

- direct feeding action of the ectoparasite;
- the associated allergic reactions by the host to the feeding or presence of the ectoparasite (hypersensitivity or 'cockle'); and
- physical damage to the skin through rubbing and scratching to relieve irritation (traumatic damage).

The last two of these are discussed below.

Hypersensitivity/cockle

Sheep chewing lice (*B. ovis*) can affect the quality of pelts and processed leather. Immediate hypersensitivity to *B. ovis* secretory/excretory products can result in a nodular skin defect called cockle, which significantly downgrades the value of the leather (Halligan and Johnstone, 1992; Heath *et al.*, 1995a, 1996). Cockle is generally detected after depilation and at the pickling stage when affected areas do not allow dye to be taken up evenly, leaving the pelt with an unattractive appearance. On sheep in which lice were removed through treatment or shearing, cockle lesions either disappear or regress on pickled pelts (Heath *et al.*, 1995a). 'Scatter cockle' describes the distribution of cockle caused by *B. ovis*, as opposed to 'rib cockle', a blemish caused by the sheep ked (*M. ovinus*).

In Ethiopia, the prevalence of cockle ('ekek') in *M. ovinus*-infested sheep pelts was shown to be 95% (Sertse and Wossene, 2005). Strong associations ($P<0.05$) were observed in sheep between cockle and infestations by *B. ovis* and *M. ovinus*. A similarly strong association ($P<0.05$) was observed in goat pelts between cockle and sarcoptic mange (*Sarcoptes scabiei* var. *caprae*) (Sertse and Wossene, 2005). The incidence of cockle has been shown to be extremely high in Ethiopia, with 71% of goats and 42% of sheep pelts in the Amhara Regional State affected. The annual economic losses due to cockle in 2002/3 at two tanneries in this region were estimated to be US$1.6 million for pickled sheep pelts and US$0.6 million for goat pelts (Sertse and Wossene, 2005).

The chrome tanned dried crust leather of scab (*P. ovis*) infested lambs shows grain surface defects such as discolorations, indurations and coarse, pitted grain (Rehbein *et al.*, 2000b). The useful (defect-free) leather size was significantly ($P<0.01$) greater for lambs treated prophylactically with an ivermectin CRC (100%) than for those with active scab infestations treated on day 84 (82.7%) or for untreated controls (7.8%) (Rehbein *et al.*, 2000b). Physical testing revealed that the leather of sheep treated prophylactically had significantly ($P<0.05$) higher thickness and elongation break and tear resistance than that of untreated controls or treated sheep with active disease; there were no significant differences in the physical characteristics of the leather between the untreated controls and sheep treated on day 84 (Rehbein *et al.*, 2000b).

Traumatic damage

The indirect effects of ectoparasites are not generally recognized. Irritation causes the animal to rub and scratch against any available object, causing physical damage to the skin and the resulting leather. Rubbing, biting and scratching as a result of chewing lice (*B. ovis*) infestation can lead to self-trauma of the skin, with resultant defects observed in the processed pelt (Durden and Mullen, 2009). Traumatic damage and cockle can often occur together. In Ethiopia, scratches and scars have been shown to have a strong association ($P<0.05$) with the presence of cockle (Sertse and Wossene, 2005).

Goat warbles (*P. silenus*) can significantly damage goat hides. Papadopoulos *et al.* (1996) examined 225 goat hides at a slaughterhouse in Thessaloniki (Greece),

and found 54.2% affected, with 27.07 (range 1.0–162) holes per hide.

Effects on the sale of stock

In Australia, sheep infested with lice (*B. ovis*) may be denied access to sale-yards, stock routes and/or agistment.

Treatment Costs

It is essential that sheep/goats should be treated as soon as possible after diagnosis of an ectoparasite, particularly a permanent ectoparasite (e.g. scab mites, *P. ovis*, or chewing lice, *B. ovis*). If diagnosis and/or treatment are delayed, the number of animals affected and/or the severity of disease increases, as does the cost of control. Effective ectoparasite control can be expensive. It has been estimated that if chewing lice (*B. ovis*) are eradicated from a flock of approximately 2000 wool-producing merinos a saving of at least AU$1000/year can be made on chemical costs.

Prevention by effective biosecurity (see Chapter 8) can significantly cut costs. Costs of prevention include regular fence inspection/maintenance, the labour required for quarantining incoming stock, the extra feed required during quarantine, veterinary costs and the costs of treating quarantined stock confirmed with an ectoparasite. The potential costs of not preventing the introduction of permanent ectoparasites into a flock/herd include the costs of: (i) purchasing the required ectoparasiticide to cure introduced infestations; (ii) the labour and materials involved; (iii) the maintenance of equipment and facilities; (iv) regular blanket treatment; (v) withdrawal periods (meat, milk, fleece); (vi) rehabilitation; (vii) extra feed of infested animals; and (viii) disposal of used dipwash. Another less direct area of financial loss is the damage to fencing, buildings and equipment through excessive rubbing and scratching.

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Appendix

Calculating the Volume of Plunge Dip Baths and Shower Dip Sumps/Tanks

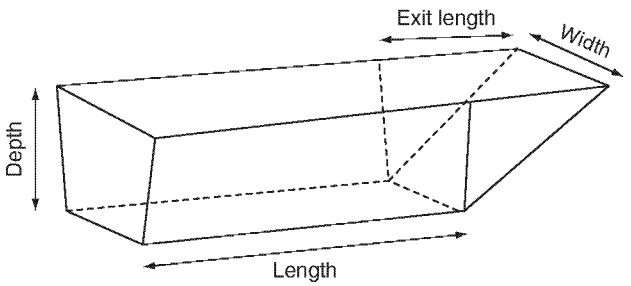

Fig. A.1. Calculating the volume of a swim-through plunge dip bath. All measurements are taken at the waterline, where there is considered to be sufficient volume to totally immerse the sheep without significant overflow. Volumes are in litres.

Volume of main section	=	Length × width × depth × 1000 l
Volume of exit	=	Exit length × width × depth × 500 l
Total dip bath volume (l)	=	Main section + exit section

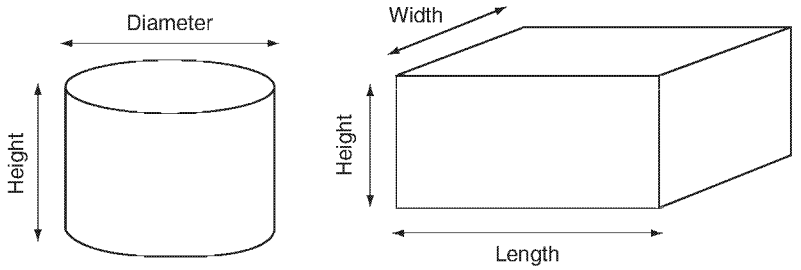

Fig. A.2. Calculating the volume of round plunge dip baths and of shower dip and jetting sumps and tanks. In the case of round dip baths, all measurements are taken at the waterline, where there is considered to be sufficient volume to totally immerse the sheep without significant overflow. Volumes are in litres.

Round dip baths and cylindrical tanks/sumps = Diameter × diameter × height
Rectangular or square tanks/sumps = Length × width × height × 1000 l

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