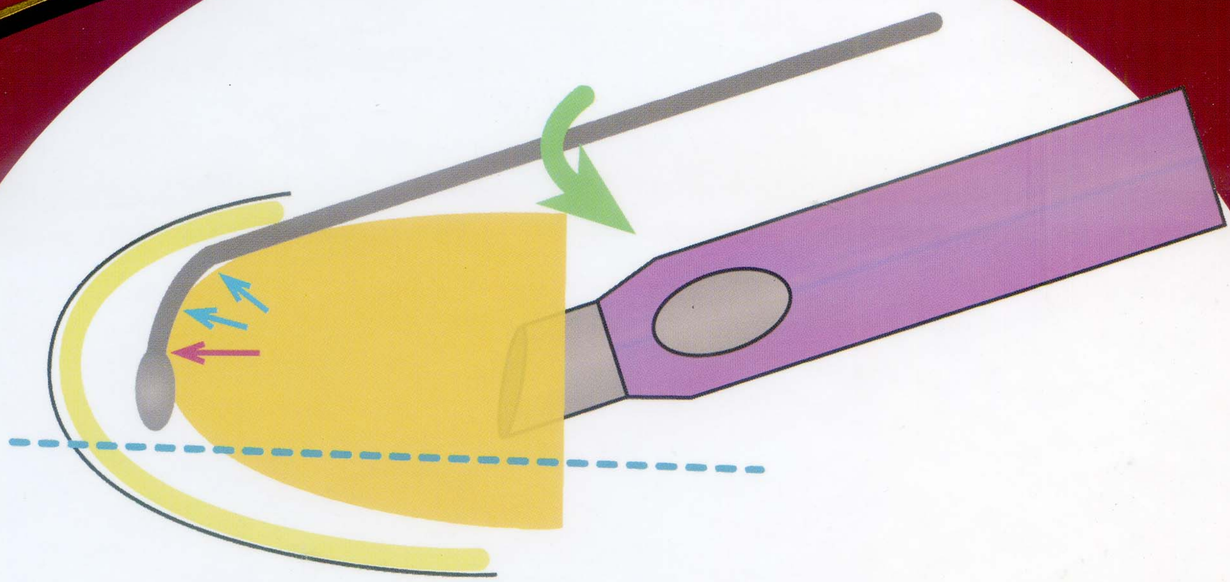
FOURTH EDITION

PHACODYNAMICS



Mastering the Tools and Techniques of Phacoemulsification Surgery

BARRY S. SEIBEL

SLACK Incorporated

FOURTH EDITION

PHACODYNAMICS

Mastering the Tools and Techniques of Phacoemulsification Surgery

10/2010
Dr. Phan Hong Mai

Barry S. Seibel, MD
Clinical Assistant Professor of Ophthalmology
University of California
Los Angeles School of Medicine

SLACK
INCORPORATED
An innovative information, education, and management company
6900 Grove Road • Thorofare, NJ 08086

ISBN-10: 1-55642-688-7
ISBN-13: 9781556426889

The procedures and practices described in this book should be implemented in a manner consistent with the professional standards set for the circumstances that apply in each specific situation. Every effort has been made to confirm the accuracy of the information presented and to correctly relate generally accepted practices. The author, editor, and publisher cannot accept responsibility for errors or exclusions or for the outcome of the application of the material presented herein. There is no expressed or implied warranty of this book or information imparted by it.

Care has been taken to ensure that drug selection and dosages are in accordance with currently accepted/recommended practice. Due to continuing research, changes in government policy and regulations, and various effects of drug reactions and interactions, it is recommended that the reader carefully review all materials and literature provided for each drug, especially those that are new or not frequently used.

The work SLACK Incorporated publishes is peer reviewed. Prior to publication, recognized leaders in the field, educators, and clinicians provide important feedback on the concepts and content that we publish. We welcome feedback on this work.

Printed in the United States

Published by: SLACK Incorporated
6900 Grove Road
Thorofare, NJ 08086-9447 USA
Telephone: 856-848-1000
Fax: 856-853-5991
www.slackbooks.com

Seibel, Barry S.,
Phacodynamics : mastering the tools and techniques of phacoemulsification surgery / Barry S. Seibel.-- 4th ed.
p. ; cm.
Includes bibliographical references and index.
ISBN 1-55642-688-7 (alk. paper)
1. Phacoemulsification.
[DNLM: 1. Phacoemulsification--methods. 2. Phacoemulsification--instrumentation. WW 260 S457p 2004] I. Title.
RE451.S364 2004
617.7'42059--dc22

2004013176

Contact SLACK Incorporated for more information about other books in this field or about the availability of our books from distributors outside the United States.

Last digit is print number: 10 9 8 7 6 5 4 3 2 1

Dedication

In loving memory of my mother,
and
In loving appreciation of my children.

Acknowledgments

As in the previous edition, I would like to first acknowledge the father of phacoemulsification, Charles Kelman, whose recent passing has cast a sense of loss on the entire field of ophthalmology; his legacy lives on not only through phacoemulsification and his many other inventions but even more so through his extraordinary spirit of innovation and determination.

John Bond and Amy McShane of SLACK Incorporated have always been trusted advisors and friends in the world of publishing through multiple editions of *Phacodynamics*; I appreciated their counsel that a new edition was again needed in response not only to new developments in the field but also to numerous requests that they had received in recent years. Lauren Plummer and Debra Toulson have played very helpful roles in organizing the many details of the new edition's production.

The nature of the technical material in *Phacodynamics* necessitates an ongoing dialogue with industry, particularly with the engineering teams. In particular, I would like to thank engineers Tom Moore, Larry Cull, Sue Kastigar, Jeff Knight, Jim Perkins, along with Tom Moore's assistant Sam Munger at Bausch & Lomb Surgical for their exhaustive efforts at rigorously proofreading the new material for technical accuracy. The same daunting task was undertaken by Alcon's David Eister, Chris Nenon, Mikhail Boukhny, and Gary Sorensen. The increased role of Phacodynamic influence on instrumentation has been facilitated by close collaboration with John Bee of Rhein Medical as well as Robert Johnston and Chuck Hess at Storz Bausch & Lomb Surgical. Larry Laks of MicroSurgical Technology provided valuable information with regard to bimanual instrumentation, an area in which he has developed innovative products. Steve Arshinoff, the foremost expert on Ophthalmic Viscosurgical Devices, provided insightful feedback on this subject, and Takayuke Akahoshi graciously provided information on his PreChop Technique. I have additionally appreciated numerous conversations over the years with fellow fluidics aficionados Terry Devine, Graham Barrett, Richard Thorlakson, and Bill Neubert.

Lecturing has continued to play a vital role in refining my understanding and consequently ability to explain Phacodynamics. As in the past, I am very grateful to the receptive audiences as well as those kind enough to have invited me to speak in the years since the last edition. Perhaps the most influential element was my inclusion on the faculty of David Chang's remarkable "Learning Phaco Chop"ASCRS and AAO course that has been rated #1 at the AAO for the past three years. I myself continue to learn each year from the extraordinary faculty including David, Randy Olson, and Skip Nichamin; they and the receptive audiences have inspired me to continually update and refine my presentations. Likewise, I have appreciated continuing to lecture with Bill Fishkind, Howard Fine, and Mark Packer at Bill's annual "Physics of Phaco" AAO course. Thanks also to Ken Rosenthal and Bob Cionni for including me on their courses. I always appreciate my contact with residents through the thoughtful invitations by Kevin Miller for my participation at the various instructional courses at the Jules Stein Eye Institute. Bausch & Lomb has been very supportive in including me in their courses over the years, including the new Baush & Lomb University organized by Rosa Braga-Mele. I have also greatly appreciated my inclusion in Alcon's unique Complementary Ophthalmic Resident Education (CORE) programs that reach out each year to hundreds of eager students around the country.

Preface to the Fourth Edition

It is hard to believe that more than a decade has passed since I made up the word "Phacodynamics" as a title to the first edition of my book, and more than five years have elapsed since the third edition. The very nature of the book was supposed to involve a certain timelessness to the extent that it sought to define the myriad of techniques and technologies into a relatively small organizational matrix based on stable logic and scientific principles. Notwithstanding the fact that the scientific community once maintained that the world was flat, it was not a change in physics that prompted this new edition but rather a substantial growth in the number of techniques and technologies of cataract surgery that could benefit from a Phacodynamic analysis.

One of the major new developments on the technology side has been the tremendous increase of emphasis on ultrasonic power modulations, prompting the numerous new diagrams and descriptions dealing with Burst, Pulse, and HyperPulse. Evolutionary pump changes and control mechanisms are noted in this new edition, and moreover the comparisons between vacuum and flow pumps were revised to be more consistent in terms of both illustrations as well as descriptions. New modalities of bimanual microincision phaco as well as AquaLase and laser phaco technologies are explained. The growing interest in and numbers of different chopping techniques prompted a considerably expanded set of diagrams and descriptions, particularly with regard to vertical chopping. A new section, Phacodynamic Complications, has been added to help coalesce the book's contents into representative clinically challenging situations. Additionally, the Phacodynamic thought process in instrument design has been expanded throughout the book, including a new appendix dealing specifically with this subject.

While the foregoing paragraph deals with the new subject material of this Fourth Edition, it does not adequately convey another major evolution from the third edition. My five additional years of teaching, answering questions, developing new instrumentation, and consulting to industry has simply fostered in me a deeper and more lucid understanding of this material. I have endeavored to convey my own enhanced knowledge into this tremendously revised new edition not only with regard to its new content but especially with regard to the extensive revisions of previous illustrations and writing throughout the book, retaining the broad cross-referencing of figures and topics that reinforces the continuity of thought underlying Phacodynamic principles.

I have been overwhelmed and humbled by the extraordinarily enthusiastic feedback that I have been fortunate enough to receive from my colleagues around the world who have read previous editions and have appreciated the material augmenting their knowledge and benefiting their patients. It is my sincere hope that my efforts in this new edition may further help my colleagues and their patients, just as many of those same colleagues have helped me through the years to refine my own understanding through questions and conversations on this subject of Phacodynamics.

Preface to the Third Edition

During the 4 years since the second edition of *Phacodynamics* was written, two significant factors have evolved which prompted this new edition. First, significant new machine technologies and surgical techniques have been introduced. Dr. Nagahara's chop technique has continued to grow in popularity and variations as the benefits of this innovative method have become increasingly apparent clinically as well as from the perspective of ultrasonic and fluidic efficiency; correspondingly, the third edition has several new illustrations and text devoted just to these chop variations. My own fault-line phaco technique was developed as an exercise in the application of phacodynamic principles with regard to surgical methodology as well as instrumentation. Similar application of phacodynamic principles was applied to the design of the Seibel Chopper, as well as the Flat-Head Phaco tip, and the logic behind these particular tools and techniques is explained in this new edition. New pumps have been developed since the previous edition, including the rotary vane pump and the scroll pump. The larger number of pumps on the phaco market has prompted this new edition's categorization of all pumps into either a flow-based or vacuum-based classification with comparison and contrast between the two with regard to clinically relevant fluidics. This classification system will help the surgeon to more knowledgeably assess new phaco machines as well as better understand the logic behind setting parameters on his or her current machine. The section on ultrasonics has greatly expanded with emphasis on new tip designs and their effect on clinical utility as well as machine fluidics. Finally, a significant new control modality is described in the third edition, the Dual Linear foot pedal, which allows simultaneous linear control of two different parameters, such as vacuum and ultrasound.

The second factor that has prompted this new edition is my 4 additional years of lecturing, during which I have continued to refine my explanations of the physics of machine technology and microsurgical technique. I am grateful to the many intelligent questions which have resulted in what I feel are even better schematic graphics and descriptions than in previous editions; over half of the illustrations and accompanying text are either completely new or revised. Moreover, my abilities in graphic illustration have continued to develop in the past 4 years, as have my computer hardware and software used in this endeavor. Finally, additional cross-referencing and categorization has been included to further reinforce the multifactorial nature of phacodynamic principles. It is this multifaceted approach to understanding the logic behind machine technology and surgical techniques which I have endeavored to carry over from previous editions and significantly enhance in this third edition.

Preface to the Second Edition

The preface to the first edition is just as relevant to this second edition: understanding the underlying principles of the surgical equipment and techniques results in maximum safety, control, and adaptability. A working knowledge of these principles has become even more vital in the past couple of years, during which time the phaco equipment has evolved to allow even greater surgical finesse and control to the operator who fully understands the parameters involved. The second edition's new section on *Anterior Chamber Fluidics* analyzes the currents involved in phaco surgery so that you can understand when and how to adjust vacuum and aspiration flow rate to achieve maximum safety and efficacy at various stages of surgery. New material has been added to the *Machine Technology* section which explains the concepts of surge, compliance, venting, bottle height function, and fluidic resistance. Understanding these concepts will not only allow an educated evaluation of the many different phaco machines on the market, but they will also maximize your effectiveness with your current machine. All of the illustrations have been carefully scrutinized for fluidic accuracy and have been revised as necessary. For example, IA tips have been changed to phaco tips in the flow diagrams because recent lab measurements have demonstrated that the flow volume depicted would not be accurate for the high resistance IA port. Even the number of drops in the drip chambers of the flow diagrams has been revised to accurately reflect the results of recent fluidic experiments. Material on Dr. Nagahara's phaco chop method as well as Dr. Koch's stop and chop method have been included in Sections Two and Three. The *Physics of Capsulorrhexis* section has doubled in size in order to include even more clinical options for different surgical situations. As in the first edition, however, the emphasis of *Phacodynamics* is not so much on individual methods or techniques as it is on the underlying principles which are common to all.

Preface to the First Edition

The fundamental goal of phacoemulsification is to remove a cataract with minimum disturbance to the eye. You should use the least number of surgical manipulations necessary to accomplish the surgery; random, superfluous movements must be actively avoided. Each maneuver should be performed with the minimum force required; maximum efficiency is attained by applying principles of physics and mechanical advantage. Physical manipulation of intraocular tissues can be decreased by taking full advantage of a phaco machine's capabilities by using principles of fluid dynamics. Minimum effort yields maximum safety.

Every phacoemulsification course teaches one or more step-by-step methods, including one-handed, two-handed, chip and flip, in-the-bag, divide and conquer, and others. Each method has its own attributes, and you should familiarize yourself with all of them. However, every step-by-step method shares the same disadvantage: not every operation will necessarily proceed in an orderly fashion to the next appropriate step. The goal of this book is to teach the fundamental principles of both the phaco machine and the microsurgical maneuvers shared by all of the step-by-step methods. By understanding these underlying principles, you will be able to transpose as necessary between methods, improvise your own methods, and adapt to virtually any surgical situation with confidence.

Foreword to the Fourth Edition

When I first learned phaco as a resident in the early 1980s, recognizing the different functions of pedal positions one, two, and three was the extent of my knowledge of Phacodynamics. Back then, many of us simply kept sculpting away in continuous mode with a fixed panel setting of 100% power, hoping all the while that we wouldn't phaco the iris or posterior capsule. Twenty years later, those early days are hard to imagine in the context of the incredible collection of technology that we now have at our disposal.

One latest generation phaco machine allows the surgeon to create 16 separate programs for phaco alone. Surgeons can select and change between programs instantaneously with the foot pedal. Within each program, we can customize virtually every parameter of our phaco machine and handpiece. Some of these parameters change automatically depending upon events in the eye, such as tip occlusion or occlusion break. The Dual Linear foot pedal (Bausch & Lomb Surgical, Rochester, NY) even gives surgeons simultaneous linear control of power and fluidics.

While such technological advances have elevated phacoemulsification surgery to a higher level than ever, such progress unfortunately comes at the expense of simplicity. It is now more complicated than ever to program a phaco machine. For some, it may seem like it could occupy an entire career just trying out the many possible permutations and combinations of settings.

Fortunately, through his textbook, Barry Seibel is there to shepherd us through the gauntlet of confusing terminology and to help us navigate the ever-expanding array of Phacodynamic features. This is the fourth edition of his classic textbook, and one can gauge the tremendous progress of phaco technology through the years by measuring the increasing thickness of each successive edition. As in the previous editions, Dr. Seibel demonstrates his unique gift for being able to simplify complex engineering concepts to a clinically understandable and practical level. His signature style of illustration gives us stepwise visual tools to understand what is otherwise happening too rapidly in real time. Most of these illustrations have been updated and enhanced.

Those who have already read earlier editions will find the same analytical approach to a number of new technologies. These range from external surge suppression strategies, such as Cruise Control (Staar Surgical, Monrovia, CA), to entirely different lens removal technologies, such as Aqualase (Alcon Laboratories, Fort Worth, TX). In addition to an expanded section on Phaco Chop, there is a brand new section devoted to phaco power modulations, such as WhiteStar (AMO, Santa Ana, CA) HyperPulse mode. Finally, Dr. Seibel has added a unique chapter dealing with Phacodynamic complications. This features a series of cases that allows readers to test their understanding with practical exercises in clinical problem solving.

For the surgeon willing to invest the time and effort in mastering Phacodynamics, there is a compelling reward—that of being able to better harness modern technology toward improving efficiency, and decreasing complications with difficult cases.

David Chang, MD

Foreword to the Third Edition

In the late 1960s when I was in the process of developing the instrumentation and procedure we now know as phacoemulsification, I found myself at the limits of that era's technology. Even today with all the advances made in computers, metallurgy, and the like, the same can be said regarding improvements in the functionality of modern phaco machines.

It is certainly fair to say that the phacoemulsification procedure relies as heavily on the surgeon's skill as it does on the apparatus. With this in mind, I have always stressed the importance of the surgeon having ample knowledge regarding the technology behind the instrumentation he or she wields.

The procedure has, from its inception, evolved in lock step with advances in technology, the most significant of which has been the introduction of microprocessor control and feedback of machine function. This advancement allows the surgeon to customize the machine to his or her own requirements. But this also implies that the surgeon have a firm understanding of the principles involved.

Dr. Seibel, in his expanded third edition of *Phacodynamics*, brings the phaco surgeon up-to-date in this marriage of technology and surgical technique. The numerous illustrations and diagrams bring the technology behind the technique to the broader ophthalmic community in a manner that is logical and concise.

Charles D. Kelman, MD
The Eye Center
New York NY

SECTION ONE

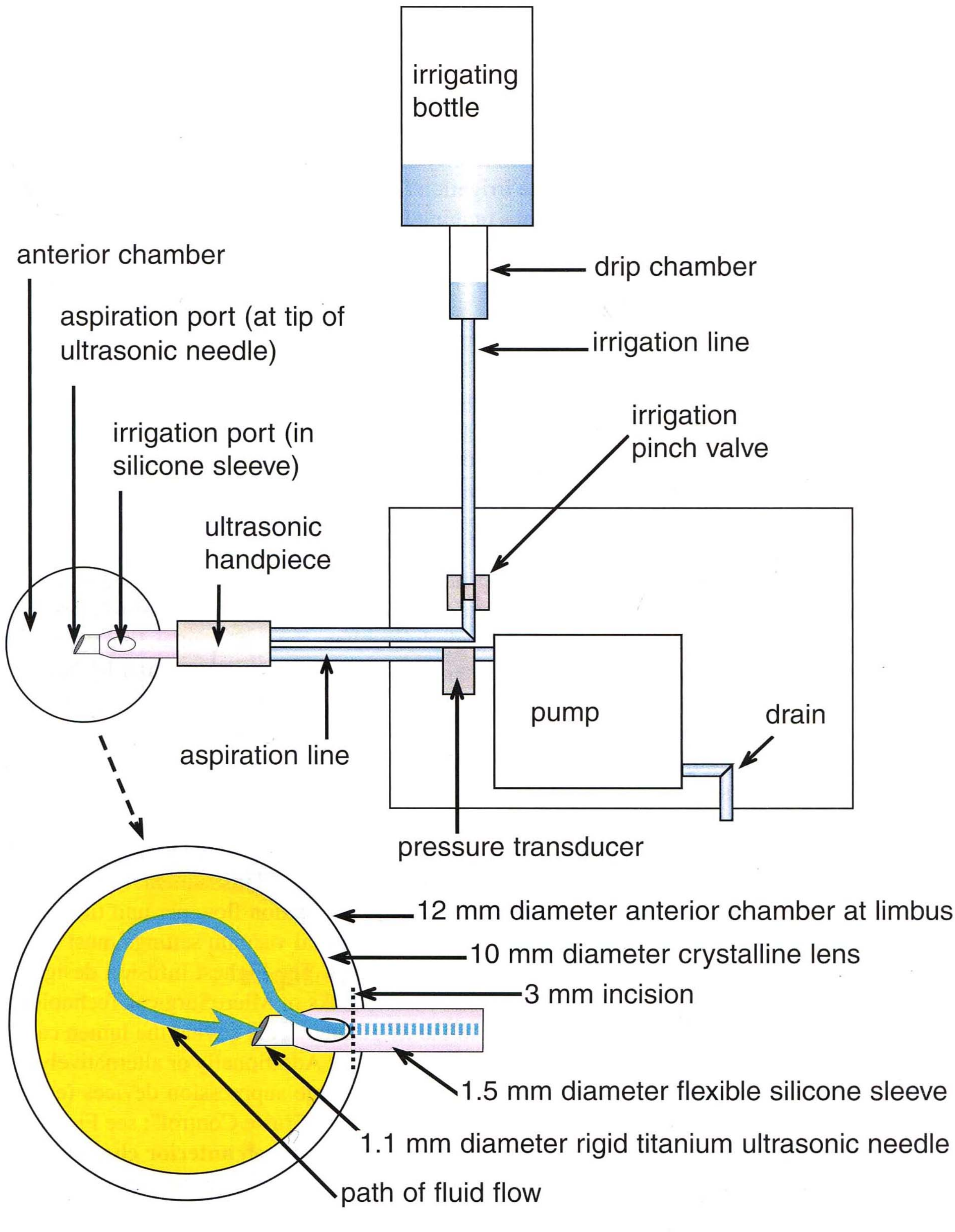
Machine Technology

Machine Overview

Phacoemulsification surgery ("phaco"), invented by Charles Kelman, MD, is comprised of two basic elements. First, **ultrasound energy** is used to emulsify the crystalline lens so that a 10 mm cataract may be removed (aspirated) through a 3 mm or smaller incision. Second, a **fluidic circuit** is employed to counteract the potential heat buildup and repulsive action of the ultrasonic needle, as well as to remove the emulsate via the aspiration port while maintaining adequate depth and pressure in the anterior chamber (Figure 1-1). This circuit is supplied via the silicone sleeve's irrigation ports by an elevated irrigating bottle that supplies both the fluid volume and pressure to maintain the chamber **hydrodynamically** (when the aspiration port is unoccluded and the pump is aspirating fluid and emulsate from the eye) and **hydrostatically** (when the pump is inactive, or when it is active with a complete occlusion of the aspiration port), respectively; anterior chamber pressure is directly proportional to the height of the bottle. Note the path of fluid flow from the irrigation line, through the ultrasonic handpiece, through the space between the silicone infusion sleeve and the ultrasonic needle, out through the irrigation ports in the silicone sleeve, through the anterior chamber, exiting through the aspiration port and through the needle lumen into the handpiece and then into the aspiration line.

The fluid circuit is driven and regulated by a pump that not only clears the chamber of emulsate, but also provides significant clinical utility. When the aspiration port at the distal phaco tip is unoccluded, the pump produces currents in the anterior chamber, measured in cc/min, which attract nuclear fragments. When a fragment completely occludes the tip, the pump provides holding power, measured in mm Hg (millimeters of mercury) vacuum, which grips the fragment to allow further manipulation such as chopping; vacuum is measured by a **pressure transducer** that usually connects to the aspiration line at or near the pump mechanism. In order to fully exploit the potential of a phaco machine, the surgeon must understand the logic behind setting the parameters of bottle height, ultrasound power, vacuum, and flow.

In understanding the machines that we will be using, we need to first ascertain whether we are using a flow pump or a vacuum pump. Furthermore, the clinical roles of flow and vacuum must be defined. The **flow rate**, or **aspiration flow rate**, is the volume of fluid per unit time that exits the anterior chamber through the phaco tip's aspiration port; it is **measured in cc or ml per minute**. The clinical role of flow is to attract lens material to the aspiration port and to remove it from the eye if that material is sufficiently small or deformable enough to fit through the phaco needle. For material that cannot deform sufficiently to be removed from the eye by aspiration outflow alone, vacuum provides the necessary deformational force, usually augmented by ultrasound energy. **Vacuum, measured in millimeters of mercury (mmHg)**, also provides the grip for lens material that is occluding the aspiration port. This grip allows ultrasound energy to more efficiently emulsify the material, and it also allows manipulation and fixation of an occluding lens fragment (eg, for chopping).



irrigating bottle
drip chamber
irrigation line
anterior chamber
aspiration port (at tip of ultrasonic needle)
irrigation port (in silicone sleeve)
irrigation pinch valve
ultrasonic handpiece
pump
drain
aspiration line
pressure transducer
12 mm diameter anterior chamber at limbus
10 mm diameter crystalline lens
3 mm incision
1.5 mm diameter flexible silicone sleeve
1.1 mm diameter rigid titanium ultrasonic needle
path of fluid flow

FIGURE 1-1

Bimanual Microincision Phaco: Alternate Irrigation Path

As illustrated in Figure 1-1, traditional phacoemulsification has irrigation and aspiration arranged coaxially on a single handpiece that enters the eye through a 3 mm incision. A second instrument such as a chopper (Figure 2-15-3) is often inserted through a separate 1 mm incision. An alternate method involves separating the irrigation from the ultrasonic aspirating tip and inserting each handpiece through separate incisions ranging from 1.2 to 1.5 mm in width. This Bimanual Microincision Phaco (a.k.a. microphaco) utilizes a bare ultrasonic needle (typically 20 Ga.) without the use of the traditional surrounding silicone infusion sleeve. Although developed decades ago, microphaco has gained in popularity just recently as newer phaco machines exploit designs that seek to limit the potential for thermal incisional injury due to friction from the bare vibrating ultrasonic needle (eg, Bausch & Lomb MicroFlow, Alcon Hyperpulse, AMO Whitestar). While aspiration still occurs through the lumen of the phaco needle, irrigation comes from a separate incision, typically in the form of an instrument such as a chopper that conducts flow through the handpiece and hollow shaft that supports the chopping tip (Figure 1-2).

Proponents of this setup cite several advantages, including the ergonomic choice of switching instruments between the two identical incisions for more choices in angles of approach to anterior chamber contents with the aspiration port. Also, having irrigation on a separate instrument allows more choices for directing the irrigating flow in order to purposely move material toward the aspiration port or alternatively to actively avoid problem areas such as weak zonules or a compromised capsule. Ultimately, of course, bimanual phaco offers the same tantalizing promise that conventional phaco took years to deliver; the potential to keep the incision small by having the intraocular lens fit through it.

Disadvantages of bimanual phaco begin with the current lack of availability of suitable lens implants that will fit through the unenlarged 1.2 mm to 1.5 mm incision, which must be enlarged to conventional phaco sizes (typically 2.5 to 3.2 mm) for insertion of current FDA approved lenses. Another relative disadvantage is the bulkier second instrument (eg, chopper), which additionally has induced drag from the attached irrigation supply line that precludes the same level of finesse that can be achieved with a conventional, more delicate second instrument. Finally, the current technology typically cannot supply the same volume of irrigation flow per unit time as compared to conventional coaxial-infusion phaco; therefore, potential vacuum settings must be lower to avoid postocclusion surge (Figures 1-48-1 through 1-48-4). The highest infusion designs currently available are the Duet handpieces designed by Larry Laks of MicroSurgical Technology, in which the chopping tip is attached peripherally to the irrigation needle so that the lumen can convey the maximum flow possible for a given gauge (Figure 1-2). Additionally or alternatively, surge can be limited with bimanual phaco by the use of various surge suppression devices (eg, small lumen phaco needles, small lumen aspiration lines, or the Staar "Cruise Control"; see Figure 1-48-4). Another way to combat surge is to augment inflow volume with an **anterior chamber maintainer** as has been described by Michael Blumenthal, MD; this device may be used in addition to or instead of an irrigating second instrument, although it involves a third incision for access to the anterior chamber (Figure 1-2).

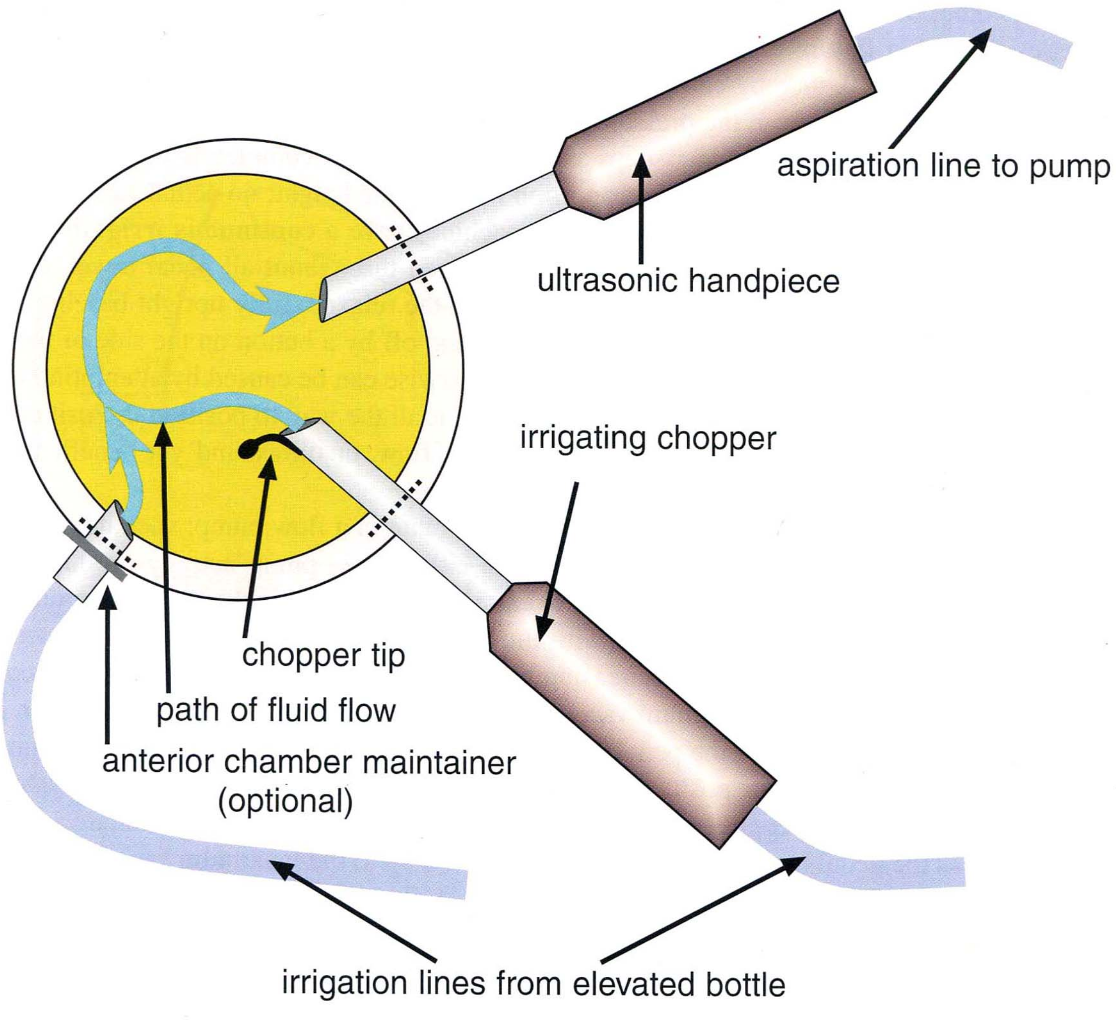

aspiration line to pump
ultrasonic handpiece
irrigating chopper
chopper tip
path of fluid flow
anterior chamber maintainer
(optional)
irrigation lines from elevated bottle

FIGURE 1-2

Foot Pedal

The phaco machine is controlled intraoperatively by the surgeon via the foot pedal. Note the four positions in phaco mode, designated 0, 1, 2, and 3 (Figure 1-3); the pump is inactive in positions 0 and 1. Note that **position 0** refers to the resting, fully upright point of foot pedal travel, whereas the other positions each refer to a particular range of foot pedal travel. The irrigation tubing passes through a fixture on the phaco machine in which a plunger pinches the tubing (see Figure 1-1) in position 0, thereby completely interrupting the fluidic circuit at this point and isolating the anterior chamber from the pressure head of the elevated irrigating bottle. When the surgeon steps into **position 1**, the plunger snaps away from the tubing, completing the fluidic circuit and pressurizing the anterior chamber in proportion to the bottle height; no actual flow is present except for any possible incisional leakage. Some machines have a **continuous irrigation mode** that eliminates position 0 by keeping the pinch valve open throughout all pedal travel, thereby pressurizing the fluidic circuit even when the pedal is in the relaxed, fully upright baseline position. The continuous irrigation mode, often toggled on and off by a button on the side of the foot pedal, prevents unexpected chamber shallowing that otherwise can be caused by attempting to lift the pedal into position 1 but instead inadvertently lifting it all the way to position 0. Position 1 is useful for many maneuvers that do not require vacuum, flow, or ultrasound yet benefit from a formed anterior chamber (eg, nuclear rotation and splitting).

As **position 2** is entered, the pump head begins to rotate in a flow pump; vacuum is created in the rigid drainage cassette of a vacuum pump. In either case, pump activity produces flow through the aspiration port when it is unoccluded, and vacuum just inside the aspiration port when it is occluded. In a vacuum pump machine with linear control, vacuum increases as the pedal is pushed further into position 2, thereby increasing both the aspiration flow rate (with an unoccluded tip), as well as the potential maximum vacuum (with an occluded tip) up to the maximum preset value, which is reached when the pedal is in the bottom of position 2. The vacuum maintains this maximum level throughout position 3 as the pedal is depressed further. In a flow pump machine with linear vacuum control of the preset vacuum limit, the maximum potential vacuum is also increased as the pedal is pushed further into position 2 up to the maximum vacuum level that is preset by the surgeon. However, flow rate (on most flow pump machines) stays constant throughout position 2 travel; the pump head can be observed to have a constant rotational speed throughout position 2 (and 3) travel. Some newer flow pump machines offer the option of linear control of either flow or vacuum while in pedal position 2. In particular, the Alcon Infiniti offers the option of linear pedal control within position 2 that switches automatically between linear flow control with an unoccluded aspiration port, and linear vacuum limit control when the aspiration port is occluded.

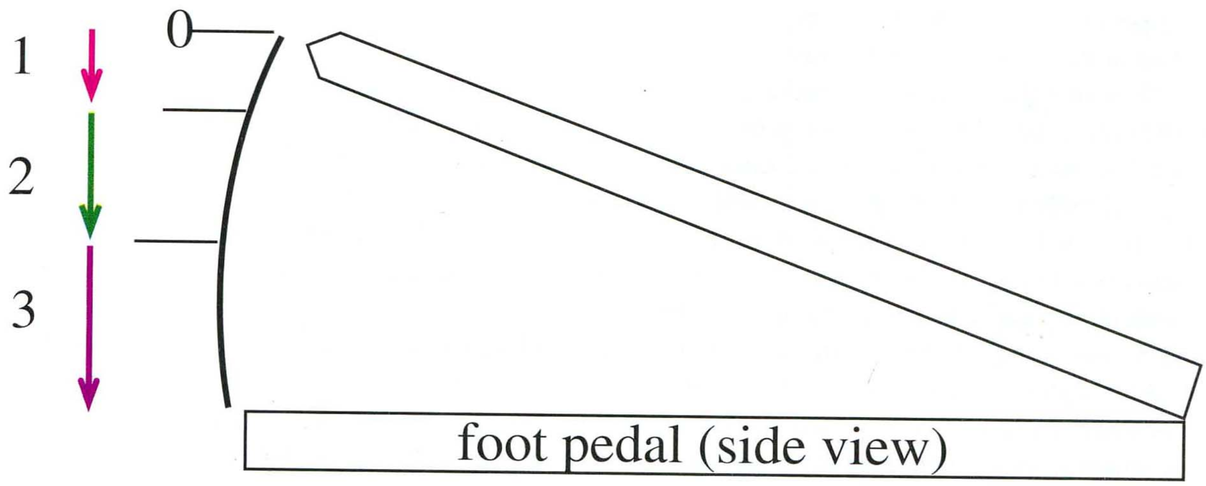


FIGURE 1-3

Foot Pedal (continued)

Position 3 represents the range in which ultrasound energy is active. A machine with linear control of ultrasound can provide progressively more ultrasound energy as the pedal is progressively depressed until the maximum amount (preset by the surgeon) is reached at the bottom of pedal travel. If the ultrasound mode is set to fixed power panel control (non-linear), the full preset ultrasound power will be abruptly engaged as soon as position 3 is entered and will be maintained throughout position 3's travel (see Figure 1-53). Another control variation involves burst-mode phaco (Figure 1-55), in which the power level is fixed by a panel preset but progressive depression of the pedal produces progressively more ultrasound bursts per second until continuous power is reached at the bottom of pedal travel.

Note that the irrigation (I; red arrows in Figure 1-4) line pinch valve that opened in position 1 continues to be open throughout positions 2 and 3. Similarly, pump activity (A; green arrows in Figure 1-4) that starts in position 2 continues throughout position 3. Many machines also have a foot pedal **reflux** control that reverses flow so that fluid (and any capsule, iris, or other inadvertently aspirated tissue) will be pushed out of the aspiration port. This reflux function is actuated on many machines by moving the pedal to one side. Some machines have an identical pedal setup for both phaco and IA (Irrigation and Aspiration), although most combine the travel of positions 2 and 3 into a single longer excursion for position 2 in IA (see lower diagram in Figure 1-4).

Although the pedal positions have heretofore been described in terms of machine function, a proper Phacodynamic analysis will include a clinical correlation to these functions. For example, many surgical maneuvers employ position 2 for holding and gripping material, such as grabbing and flipping the epinucleus (as described by Howard Fine, MD) so that it can be aspirated while it is not juxtaposed to the capsule in order to enhance safety (Figure 2-20). Once it is thus positioned, it can be aspirated by pressing the pedal further so that position 3 is engaged. Therefore, in this scenario, the surgeon has at his or her disposal **two** valuable and **distinct clinical functions**, that of **gripping** and manipulating (position 2) **and** that of **aspirating** material (position 3). However, in order to achieve this clinical utility, the parameter of vacuum must be set appropriately for the particular density of a given epinucleus. If it is arbitrarily set too high, the vacuum alone in position 2 will produce abrupt aspiration of the epinucleus immediately upon contact, decreasing the safety margin because of the juxtaposed capsule. The surgeon in this scenario would therefore only have one clinical function (aspiration) at his or her disposal because such a high vacuum setting deprives the surgeon of the two separate clinical functions of gripping and aspirating that were achieved with pedal positions 2 and 3 respectively when the vacuum was set appropriately.

An alternate control strategy in this setting would be using lower linear vacuum in position 2 to grip the epinucleus, and then depressing the pedal further in position 2 to create higher vacuum and aspiration, without engaging ultrasound in position 3. This alternate strategy retains the Phacodynamic advantage of two distinct clinical functions; gripping with lower linear vacuum levels, and aspiration with higher linear vacuum levels. However, by using higher vacuum for aspiration in position 2 rather than a lower vacuum setting augmented by mild ultrasound in position 3 as described previously, the potential for surge is greater (see Figures 1-48-1 through 1-48-3).

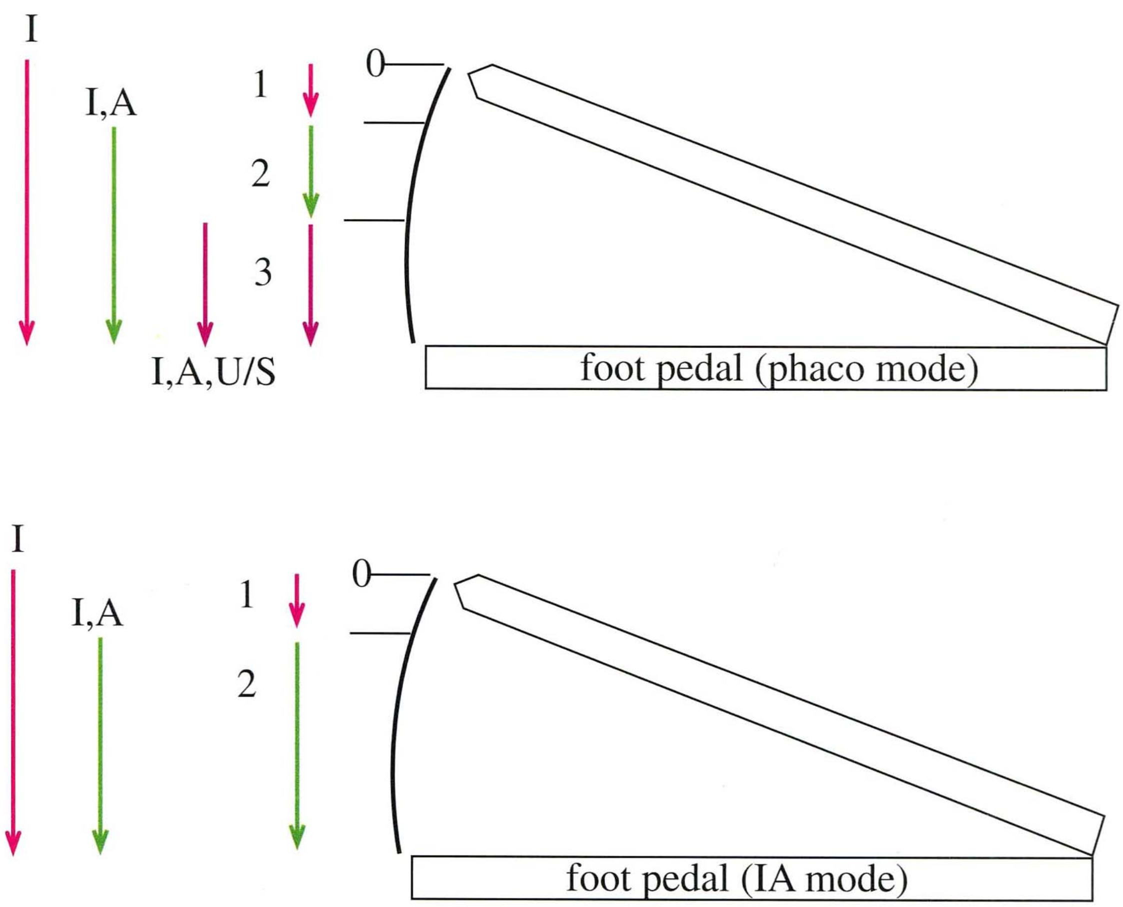

I
I,A
1
2
3
0
I,A,U/S
foot pedal (phaco mode)
I
I,A
1
2
0
foot pedal (IA mode)

FIGURE 1-4

Foot Pedal (continued)

As has been discussed, a standard phaco pedal has fluidics and ultrasound located sequentially within a single plane of travel, oriented up-and-down, or in pitch (see Figure 1-3). This configuration has two relative liabilities. First, each parameter of fluidics and ultrasound has a relatively small range of pedal travel and therefore limited control sensitivity; pushing the pedal a small distance quickly traverses whatever range of linear control that might be present, making it challenging to try to accurately command an intermediate level. Second, even if linear control of vacuum is present in position 2, only the maximum vacuum level is typically carried into and throughout position 3's ultrasound function, thereby often precluding a correct and balanced titration of both parameters.

The **Dual Linear Pedal** (Bausch & Lomb Surgical Millennium) overcomes these liabilities by separating fluidics and ultrasound into two planes of pedal movement, pitch (up-and-down) and yaw (side-to-side), as seen in Figure 1-5. This design offers enhanced control sensitivity because of the increased range of travel for both fluidics (either vacuum or flow) and ultrasound. Even more importantly, the parameters may be simultaneously and independently controlled in a linear fashion, so that the surgeon may, for example, choose high vacuum and high ultrasound for initially impaling the heminucleus, high vacuum and no ultrasound for gripping and centrally displacing the heminucleus, moderate vacuum and no ultrasound for the actual horizontal chop, and then moderate vacuum and moderate ultrasound for carouseling phaco-aspiration of the chopped fragment. This level of Phacodynamic control is not available with a conventional pedal, although the Dual Linear Pedal may be configured for use as a conventional pedal for those surgeons who prefer this modality.

Although all Dual Linear illustrations in this book depict pitch controlling position 2 (vacuum) and yaw controlling position 3 (ultrasound), these functions can be reversed if so desired by the surgeon. However, pitch is a somewhat more ergonomic motion compared to ankle inversion/eversion (yaw). Furthermore, modern techniques such as chopping depend more on frequent application of a wide range of vacuum levels and less frequent applications of mild to moderate ultrasound. Therefore, utilizing pitch, with its greater ergonomics and range of travel (therefore enhanced control sensitivity), for vacuum may make more sense for the chopping surgeon.

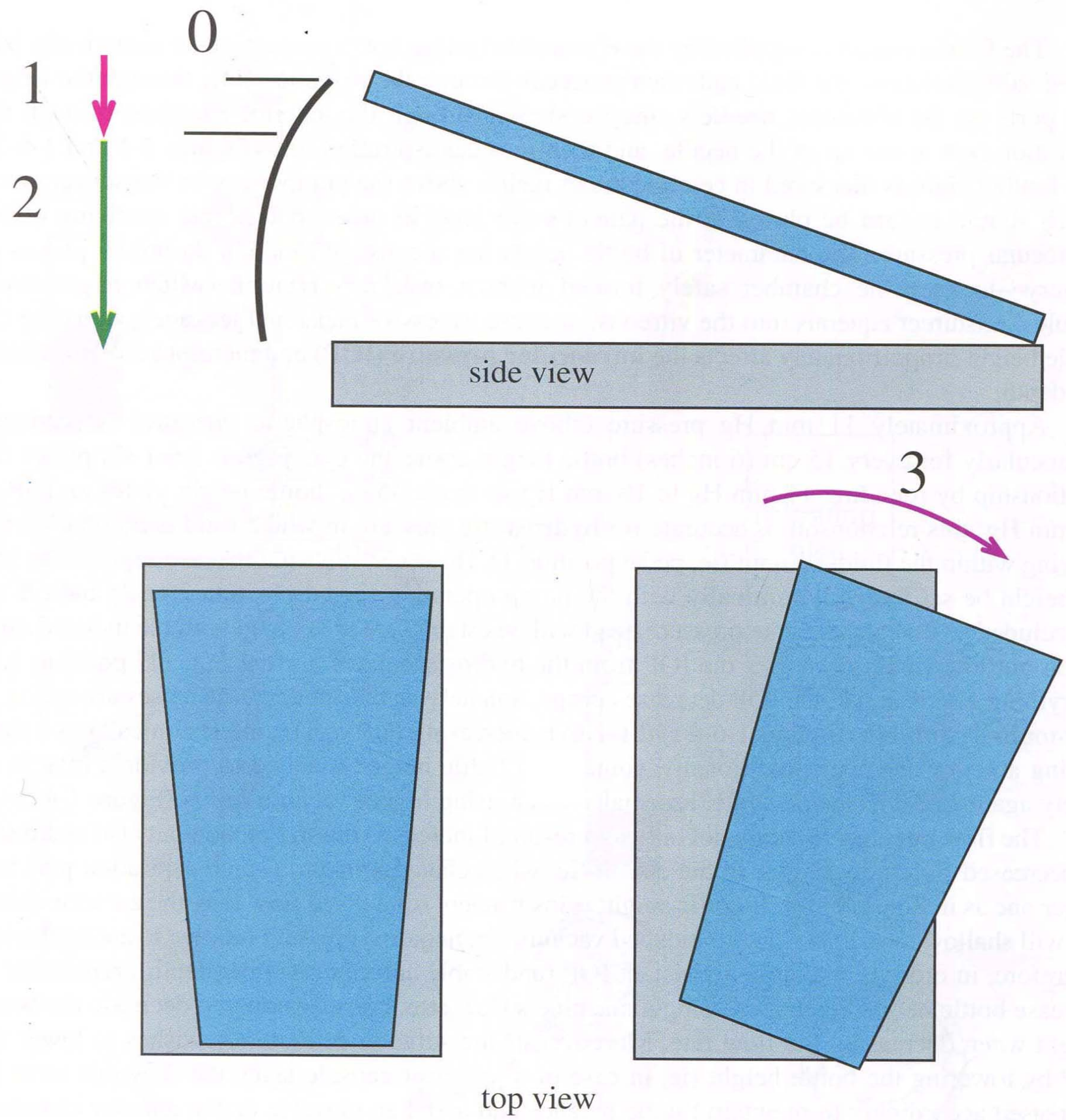


FIGURE 1-5

Irrigating Bottle

The fluidic circuit is supplied by the elevated irrigating bottle containing an osmotically balanced saline solution; the fluid path then proceeds through the irrigation line, through the irrigation ports on the ultrasonic needle's silicone sleeve, through the anterior chamber, through the aspiration port at the tip of the needle, and then into the aspiration line (Figures 1-1 and 1-6-2). The bottle height is measured in centimeters or inches above the pump/pressure transducer array, which should in turn be placed at the patient's eye level in order to facilitate modeling of the intraocular pressure. The parameter of bottle height has a constant function during all phases of surgery—to keep the chamber safely formed without overpressurization (which might stress zonules, misdirect aqueous into the vitreous, or cause excessive incisional leakage); adjusting the bottle height proportionately affects the **intraocular pressure (IOP)** and therefore anterior chamber depth.

Approximately 11 mm Hg pressure (above ambient atmospheric pressure) is produced intraocularly for every 15 cm (6 inches) bottle height above the eye. Figure 1-6-1 simplifies the relationship by rounding 11 mm Hg to 10 mm Hg so that a 45 cm bottle height yields an IOP of 30 mm Hg; this relationship is accurate for **hydrostatic** pressure in which fluid is present but not moving within the fluidic circuit (ie, pedal position 1). However, it is vital that the appropriate bottle height be set **hydrodynamically** with the pump operating (pedal position 2 or 3) and the tip unoccluded so that an adequate pressure head will be established to keep up with the induced aspiration outflow which decreases the IOP from the hydrostatic level present in pedal position 1. If everything else is equal, the IOP decreases proportionately as the flow rate increases according to **Bernoulli's equation** (Figures 1-6-2 and 1-10A); decreasing IOP will manifest clinically as a shallowing anterior chamber. Additionally, some extra bottle height is added to provide a margin of safety against postocclusion surge, especially when using higher vacuum levels (Figure 1-48).

The flow rate may increase not only as a result of increased pump function but also as a result of decreased fluidic resistance in the circuit (ie, when changing from a small aspiration port to a larger one as in Figure 1-44). If bottle height is insufficient for a given flow rate, the anterior chamber will shallow or collapse due to induced vacuum (ie, negative pressure relative to atmospheric). Therefore, in order to maintain a constant IOP (and stable anterior chamber depth), remember to increase bottle height when increasing a machine's flow rate; correspondingly, decrease the bottle height when decreasing the flow rate. Moreover, if the surgeon deliberately wishes to lower the IOP by lowering the bottle height (ie, in case of a posterior capsule tear), the flow rate must be decreased accordingly to maintain fluidic balance and avoid an unstable or flat anterior chamber.

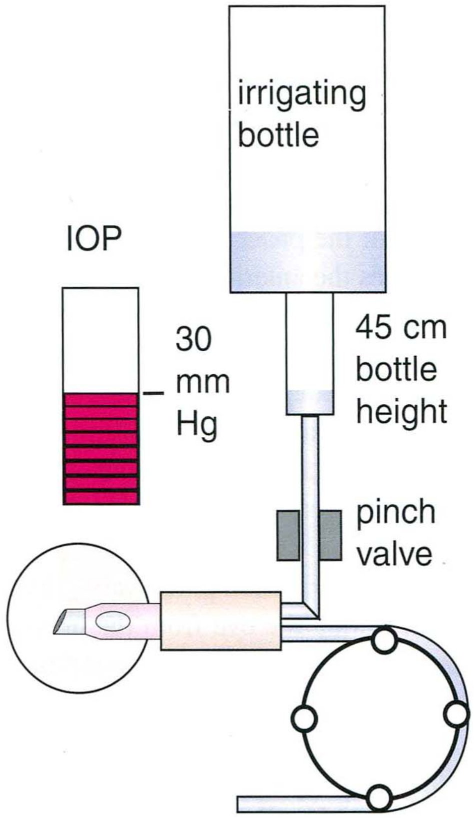


Figure 1-6-1

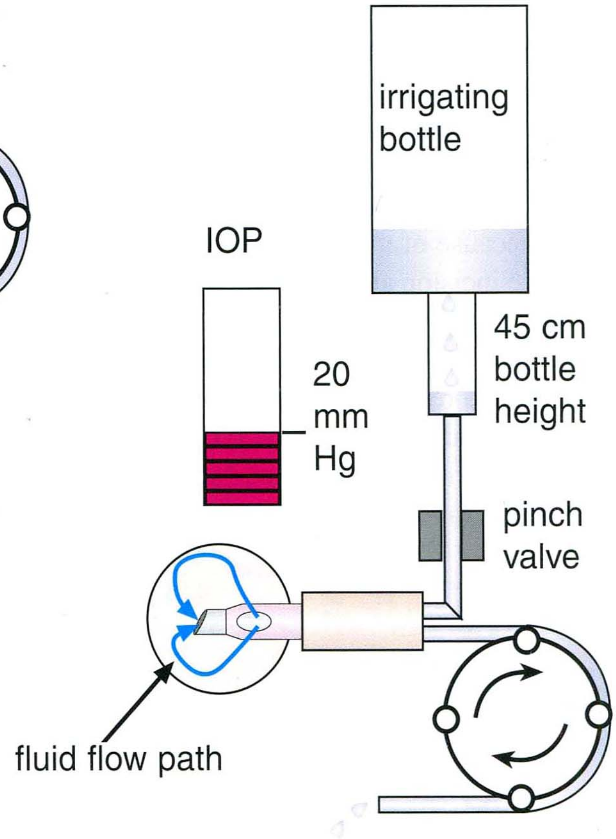


Figure 1-6-2

FIGURE 1-6

Irrigating Bottle (continued)

When the aspiration port becomes occluded, the IOP will rise to the hydrostatic level established by the bottle height even in position 2 or 3 (Figure 1-7-1) except to the extent that vacuum or ultrasound eventually clears the occlusion in these positions, respectively. Note in Figure 1-7-1 that the pump wheel is rotating but no flow is present; no drops are present at the drain or in the drip chamber. The absence of flow is secondary to the occlusion of the phaco tip's aspiration port by a large piece of nucleus. Occlusion of the aspiration port isolates the anterior chamber from the aspiration line and the pump; this isolation results in identical IOPs of 30 mm Hg in both Figures 1-6-1 and 1-7-1 even though the pump is operating in the latter but not in the former. This situation of a moving pump head with a complete occlusion and absence of flow is typically accompanied by venting (Figure 1-15) in order to modulate aspiration line vacuum and prevent it from exceeding the preset limit. Furthermore, modern phaco machines will actually decrease or eliminate pump activity when complete occlusion and absence of flow is detected (see Figure 1-16 on eye model and pressure transducer).

When the pedal is in its baseline non-depressed position 0, the irrigation pinch valve (located on the machine at approximately eye level) is closed, thus isolating the eye from the pressure head established by the column of fluid (bottle height) between the pinch valve and the top of the fluid in the irrigating bottle drip chamber (Figure 1-7-2). The anterior chamber will become shallow in position 0 because of unopposed vitreous pressure; indeed, the IOP approaches 0 mm Hg to the extent that the incision allows communication with ambient atmospheric pressure. Although this chamber shallowing and subsequent nuclear prolapse was intentionally used in the original Kratz-Maloney phaco technique, most modern methods (eg, four quadrant, chopping) are best served by a constantly pressurized chamber such as that which is achieved with **continuous irrigation mode**, which eliminates position 0 (Figure 1-3). Because the chamber can collapse without the pressure head provided by the elevated irrigating bottle, especially in pedal position 2 or 3, the operating room staff must be vigilant in not allowing the bottle to run out of fluid during an operation.

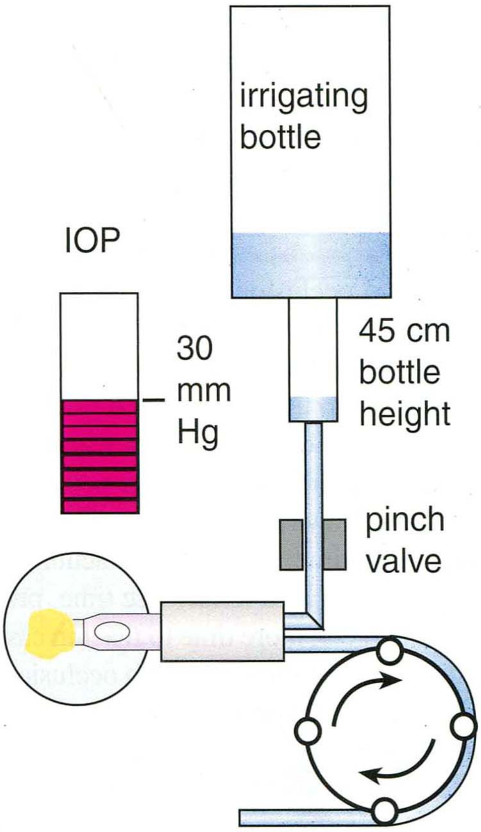


Figure 1-7-1

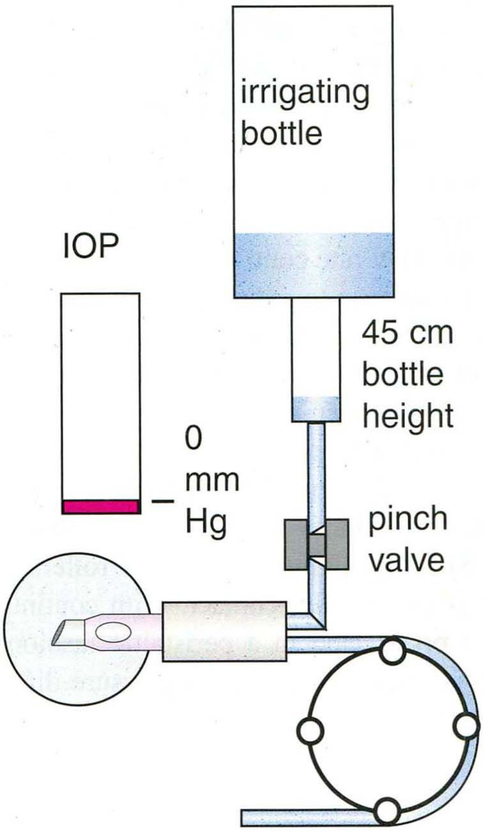


Figure 1-7-2

FIGURE 1-7

Flow Pumps: Overview and Peristaltic Pump

The flow pump, also known as a positive displacement pump, physically regulates the fluid flow in the aspiration line via direct contact between the fluid and a rotating element (pump head) in the pump mechanism; this is in contrast to a vacuum pump, which has an air interface in its drainage cassette that indirectly links the aspiration line fluid to the pump mechanism (Figure 1-25). With a flow pump, the surgeon commands an **aspiration flow rate** in cc per minute and also sets a **vacuum limit** in mm Hg. The vacuum limit does not command the machine to automatically produce that level of vacuum but rather limits vacuum buildup beyond that level when the aspiration port is occluded. Therefore, flow pumps attempt to maintain the commanded flow rate while vacuum varies with fluidic resistance (eg, the degree of tip occlusion) up to the vacuum limit. When setting flow rate in a flow pump, the surgeon is actually setting the rotational speed of the pump head (measured in revolutions per minute, or rpm). When the aspiration port is completely unoccluded, the actual aspiration outflow rate is proportional to this commanded flow rate or pump speed. By increasing pump speed with the machine's flow rate control, nuclear fragments are more strongly and rapidly attracted to the phaco tip. However, even with complete occlusion of the phaco tip, and consequent interruption of aspiration outflow, flow rate control is still a useful parameter because it proportionately varies the **rise time**—the time required for vacuum to build to the preset limit once the tip is completely occluded. For example, a longer rise time, produced by a slower commanded flow rate (pump speed) gives the surgeon more time to react in case of inadvertently occluded material, such as iris or capsule. Regardless of the state of tip occlusion, adjusting the flow rate control of a flow pump determines the rotational speed of the pump head, allowing the surgeon to adjust the overall character of the machine from relatively slow and gentle (slow rotational speed of 15 to 25 cc/min) to faster and more aggressive (35 to 50 cc/min). The presence of an independent flow rate control further differentiates a flow pump from all current vacuum pumps used in phaco surgery.

The two current phaco flow pumps are the peristaltic pump and the scroll pump (Concentrix module, Bausch & Lomb Millennium). The peristaltic pump is the most commonly employed in current phaco machines and serves as a good schematic example of the flow pump's principles (Figure 1-8). As the pump head rotates, rollers engage the stationary aspiration tubing and collapse it at each point of roller contact. With continued rotation, boluses of fluid are created between rollers and propagated in a peristaltic fashion in the direction of rotation as indicated by the arrows. This fluid flow creates a pressure differential at the beginning of the pump head which draws more fluid from the aspiration tubing.

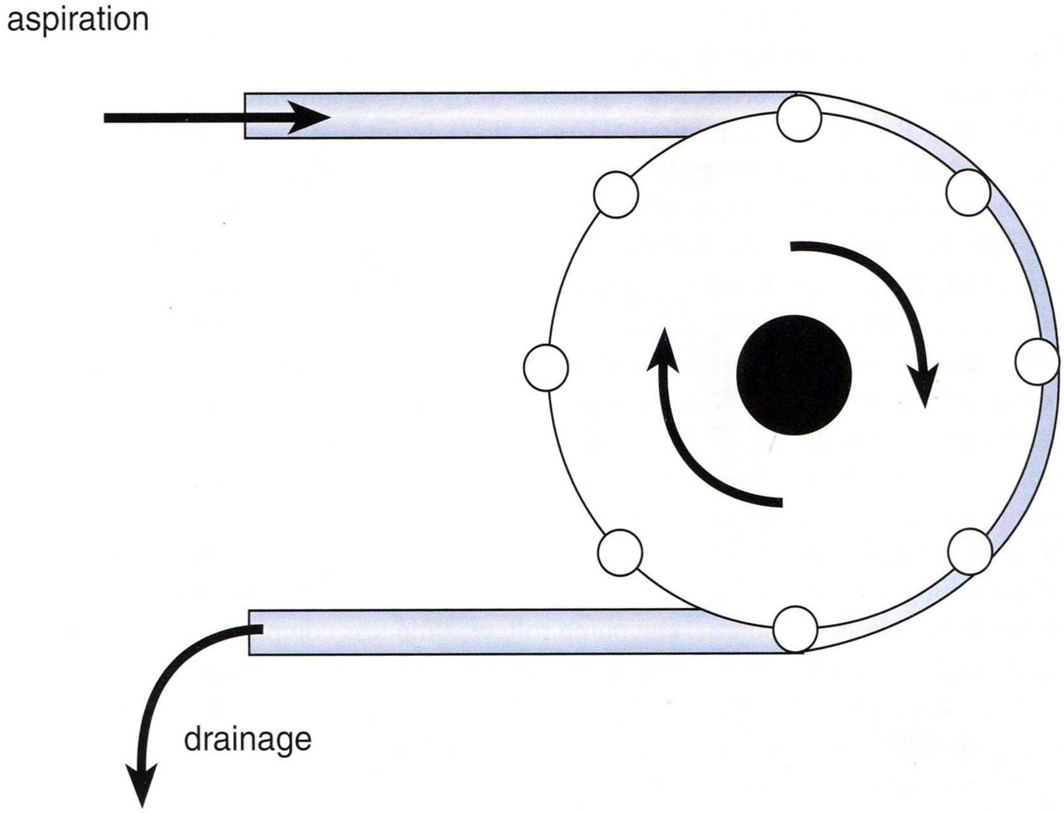


FIGURE 1-8

Scroll Pump

Older peristaltic pumps have some relative liabilities inherent to their basic design. First, fairly compliant aspiration tubing is required so that the pump head rollers can collapse the tubing and milk boluses of fluid through it; however, increased compliance in the fluidic circuit increases the potential for surge problems (see Figures 1-47 and 1-48-1). Second, the indirect contact between the fluid and rollers via the tubing, as well as imperfect apposition of the collapsed internal tubing walls, may allow for pump leakage (a.k.a. poor volumetric efficiency) in which the pump rollers traverse the aspiration line faster than the fluid inside of the line; at a given rotational pump speed, the actual flow rate decreases as resistance to flow (vacuum) increases (see Figure 1-11). The scroll pump (Bausch & Lomb Surgical Concentrix) design addresses these problems by placing a rigid, orbitally rotating pump element directly within the fluidic circuit (Figure 1-9). The scroll element and pump housing as illustrated are fixed between two rigid flat plates to confine the fluid into the scroll channels. Relative to a conventional peristaltic pump, a scroll pump can utilize less compliant tubing which only needs to be flexible enough to allow ergonomic control of the ultrasonic and IA handpiece; the less compliant tubing has less of a potential for surge problems (see Figures 1-47 and 1-48-1). Furthermore, by eliminating compliant tubing as an integral pump element, the scroll pump can be manufactured to tighter tolerances which decrease the potential for pump leakage, especially at higher vacuum levels. As a result of its low compliance and minimal leakage, the scroll pump is particularly well suited to having the option of being used in a vacuum emulation mode as discussed with Figure 1-32.

More recent peristaltic designs have overcome previous limitations by such adaptations as bicompliant tubing, a hybrid aspiration line tubing (Alcon Legacy, AMO) which uses softer, more compliant tubing only at the point of the pump rollers while less compliant (more rigid) tubing is used on the much greater length between the pump and the handpiece to limit surge potential. The Alcon Infiniti has a Fluid Management System that eliminates tubing over rollers by utilizing a sealed rigid cassette with a stiff polymer membrane over which the pump head rollers traverse, thereby minimizing compliance and maximizing responsiveness. Bausch & Lomb's Advanced Flow System uses software control algorithms to compensate for leakage, thereby enhancing volumetric efficiency. Moreover, this control over volumetric efficiency allows even greater ability to alter the character of the machine from slow and gentle to fast and more aggressive, depending on surgeon preference.

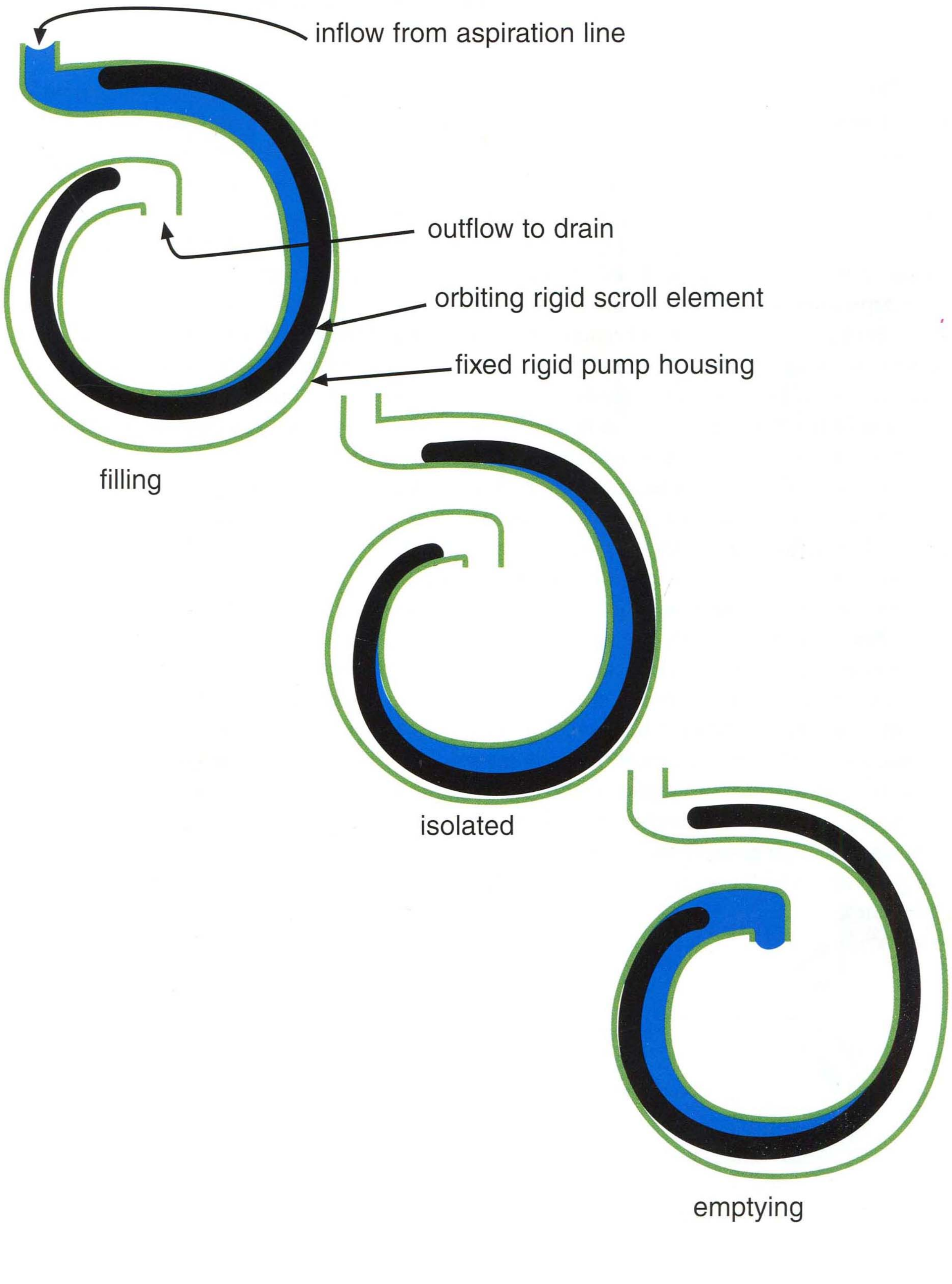

inflow from aspiration line
outflow to drain
orbiting rigid scroll element
fixed rigid pump housing
filling
isolated
emptying

FIGURE 1-9

Flow Pumps: Direct Control of Flow and Indirect Control of Vacuum

The ability of adjusting the aspiration flow rate allows the flow pump surgeon to control the anterior chamber currents that draw nuclear material to the aspiration port from gentler and slower (Figure 1-10-1) to stronger and faster (Figure 1-10-2). This direct control of flow with flow pumps has an indirect but predictable effect on vacuum in the fluidic circuit. When a flow pump is set to a low rotational speed (ie, low commanded flow rate), the subsequent low flow rate does not produce any appreciable vacuum in the aspiration line unless the aspiration port is occluded. Indeed, at lower flow rates with an unoccluded phaco aspiration port, there is a positive pressure in the aspiration line because of the pressure head from the irrigation bottle (Figures 1-10-1 and 1-23); fluid flows as illustrated because of the **pressure differential** between the higher positive pressure of the anterior chamber and the lower (but still positive relative to atmospheric) pressure in the aspiration line. The flow rate is increased in Figure 1-10-2, and **vacuum** (measured in mm Hg below atmospheric pressure, indicated by a negative value on the graph) is produced in the aspiration line because of the resistance induced by the aspiration port (especially with a 0.3 mm IA tip or a partially occluded aspiration port on a standard 19 Ga. phaco tip) and, to a lesser extent, by the aspiration tubing's inherent resistance, which is a function of its length and internal diameter. At slower flow rates, these resistances are negligible.

Note that the flow rate can be visually estimated by observing the irrigating bottle's drip chamber, which is a direct correlate of the anterior chamber fluid current in terms of strength and speed. Note also that because the resistances of the phaco needle and tubing are located between the pump and the aspiration port, this is the location of greatest vacuum buildup or **negative pressure** (mm Hg below atmospheric pressure). The portion of the fluidic circuit between the irrigating bottle and the aspiration port, including the anterior chamber, will have a more positive pressure because of the pressure head from the irrigating bottle. Moreover, this portion of the fluidic circuit will always have a positive value (measured in mm Hg above ambient atmospheric pressure) when the anterior chamber is formed; chamber collapse is indicative of too low a bottle height (not enough positive pressure) or too rapid a flow rate (too much induced vacuum or negative pressure) which results in a net negative intraocular pressure (ie, below ambient atmospheric pressure).

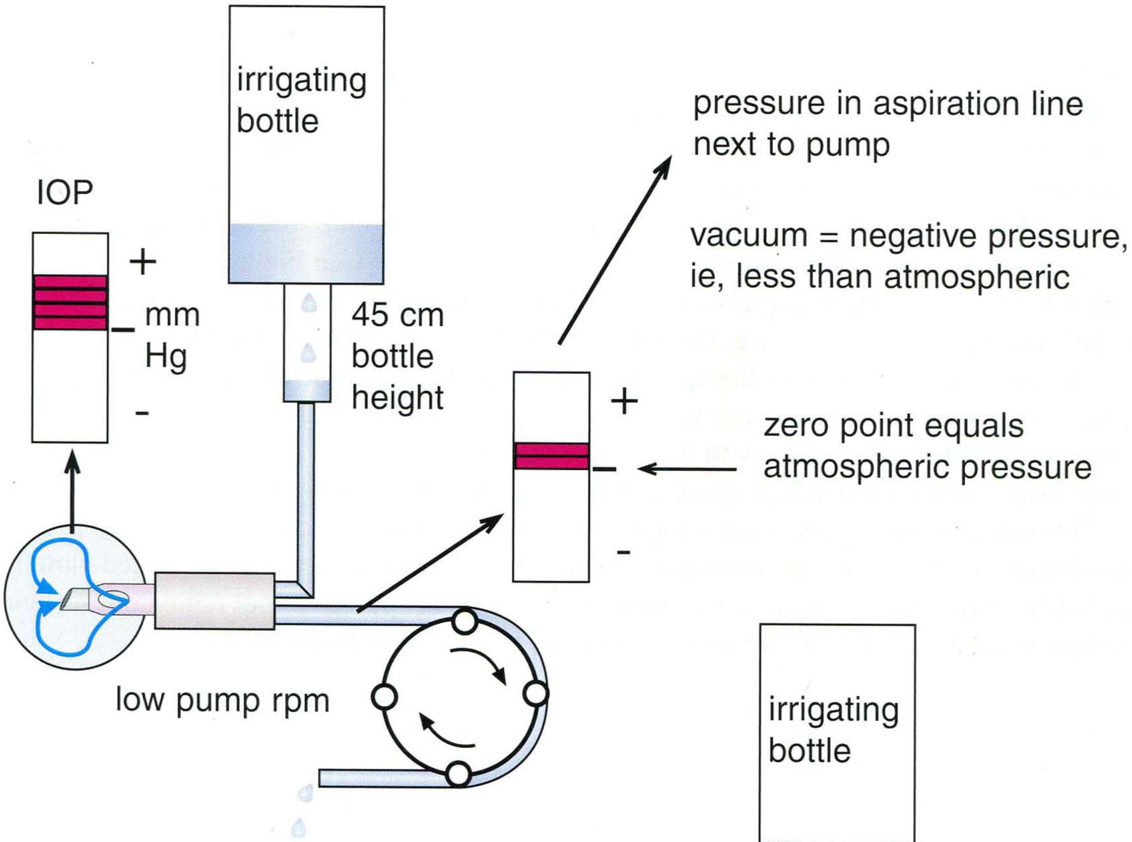


Figure 1-10-1

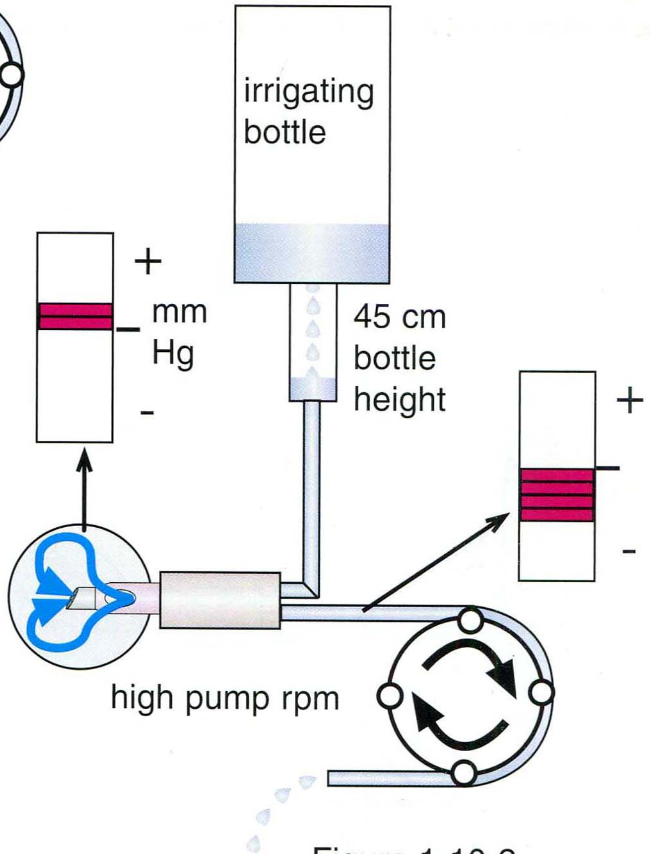


Figure 1-10-2

FIGURE 1-10A

Flow Pumps: Direct Control of Flow and Indirect Control of Vacuum (continued)

If the aspiration line was removed from the pump and simply left open to atmospheric pressure at the same level as the eye, a baseline flow would still be produced because of the pressure head from the elevated irrigating bottle (see Figures 1-44 and 1-45); in this scenario, the **aspiration line pressure (ALP)** would be identical to the IOP. If the flow pump is then reconnected and driven at a speed that produces a flow greater than the baseline value, the ALP will be less than the IOP as the pump pulls on the fluid to produce the faster flow (see Figures 1-10-1 through 1-10-3). However, a flow pump can also act as a **flow regulator** in that it can decrease the flow below the baseline level; in this case, the IOP and the ALP are identical (Figure 1-10-4), assuming both the eye and the aspiration line are at the same height below the elevated irrigating bottle, the higher pressure of which is driving the fluidic circuit. Because fluid flow is interrupted where the flow pump head interdigitates with the fluidic circuit (see Figures 1-8 and 1-9), flow cannot occur any faster than the rotational speed of the pump head regardless of how high the bottle is placed. This is in contrast to a venturi pump, in which the indirect linkage of air via the drainage cassette (Figure 1-25) allows an increased bottle height to translate into an increased flow rate (Figure 1-43). Therefore, as opposed to a flow pump, a venturi pump cannot regulate flow below the baseline value that is driven by the pressure head from a given bottle height.

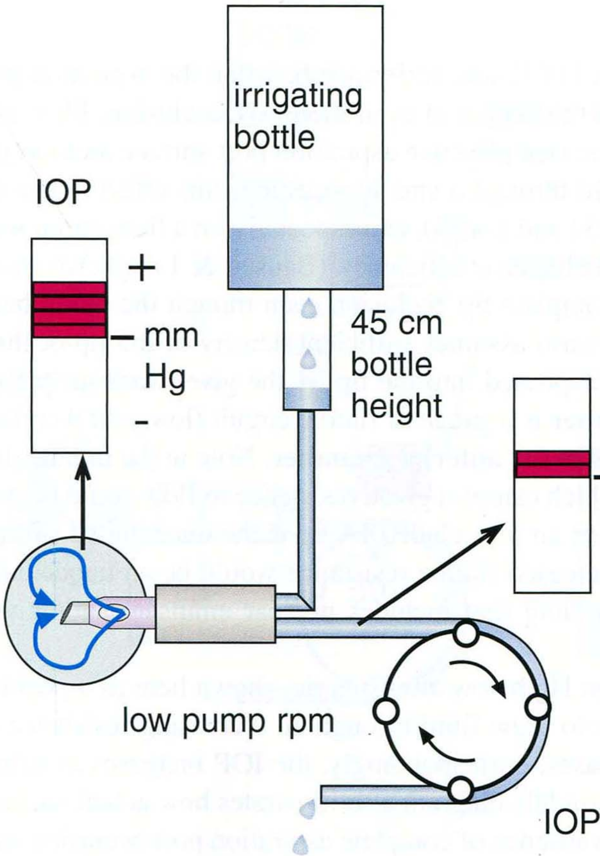


Figure 1-10-3

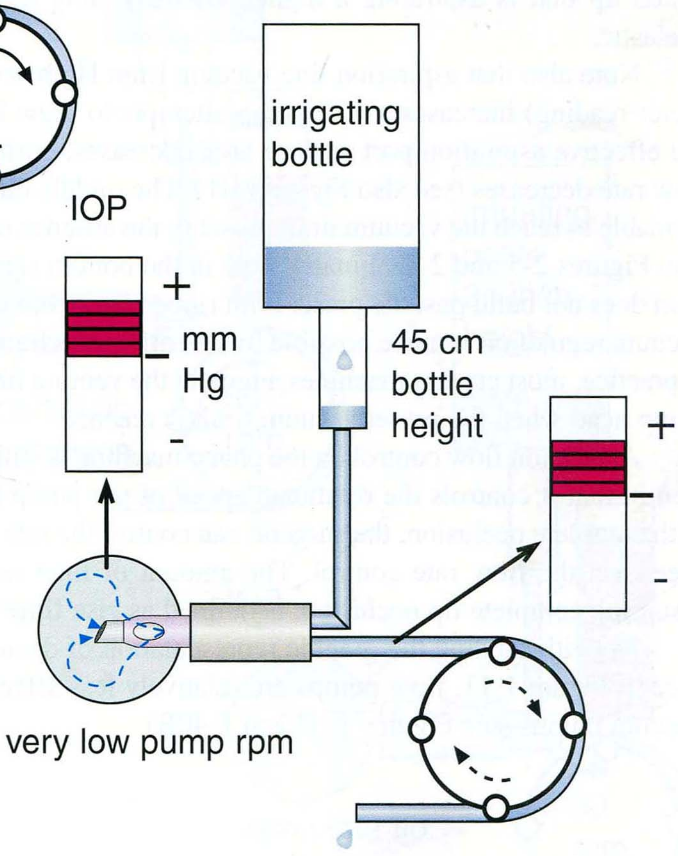


Figure 1-10-4

Figure 1-10B

Flow Pumps: Tip Occlusion Effects on Flow and Vacuum

Actual fluid flow is dependent on the level of fluidic resistance between the aspiration port and the pump, which in turn is often related to the degree of aspiration port occlusion. Flow rate decreases with increasing tip occlusion (ie, decreased effective aspiration port surface area) as the pump attempts to pull the same amount of fluid through a smaller opening; this effect is less on flow pumps than on vacuum pumps (Figures 1-34 and 1-40B), and especially on a flow pump with flow loss compensation software to enhance volumetric efficiency (Bausch & Lomb Advanced Flow System). Flow ceases completely with complete tip occlusion even though the pump head may continue to rotate (Figure 1-11). This scenario assumes sufficient density of the tip-occluding fragment such that it is not deformed and aspirated into the tip by the given vacuum preset. The activity in the **irrigating bottle drip chamber** is a gauge of fluidic circuit flow, and therefore **mirrors the strength and rapidity of currents in the anterior chamber**. Note in the middle diagram that a given aspiration port surface area which causes a given resistance to flow could be produced either by a partially occluded phaco tip or an unoccluded IA tip if the unoccluded surface area is equivalent in each. Another cause of increased fluidic resistance would be an unoccluded phaco tip that is aspirating a higher viscosity fluid that includes nuclear emulsate and/or viscoelastic.

Note also that aspiration line vacuum (mm Hg below atmospheric, shown here as a positive meter reading) increases as the pump attempts to draw fluid through an increasing resistance as the effective aspiration port surface area decreases; correspondingly, the IOP increases as actual flow rate decreases (see also Figure 1-41). The middle diagram also illustrates how actual vacuum is unable to reach the vacuum limit preset in the absence of complete aspiration port occlusion (see also Figures 2-5 and 2-6). Finally, note in the bottom right schematic in Figure 1-11 that the vacuum does not build past the preset limit (green bar) even though the pump head is still turning; this vacuum regulation is made possible by a **venting mechanism** (see Figures 1-15 and 1-46). In actual practice, most current machines augment the venting mechanism by slowing and/or stopping the pump head when the preset vacuum limit is reached.

Aspiration flow control on the phaco machine is still important even with complete tip occlusion in that it controls the rotational speed of the pump head. Even though no actual flow exists with complete occlusion, the surgeon can control the rate of vacuum buildup by variation of pump speed via the flow rate control. The amount of time required to reach a given vacuum preset, assuming complete tip occlusion, is defined as **rise time** (Figure 1-13).

Notwithstanding the graphic representation of decreasing flow with increased fluidic resistance in Figure 1-11, flow pumps are relatively less affected by this phenomenon as compared to vacuum pumps (see Figures 1-34 and 1-40B).

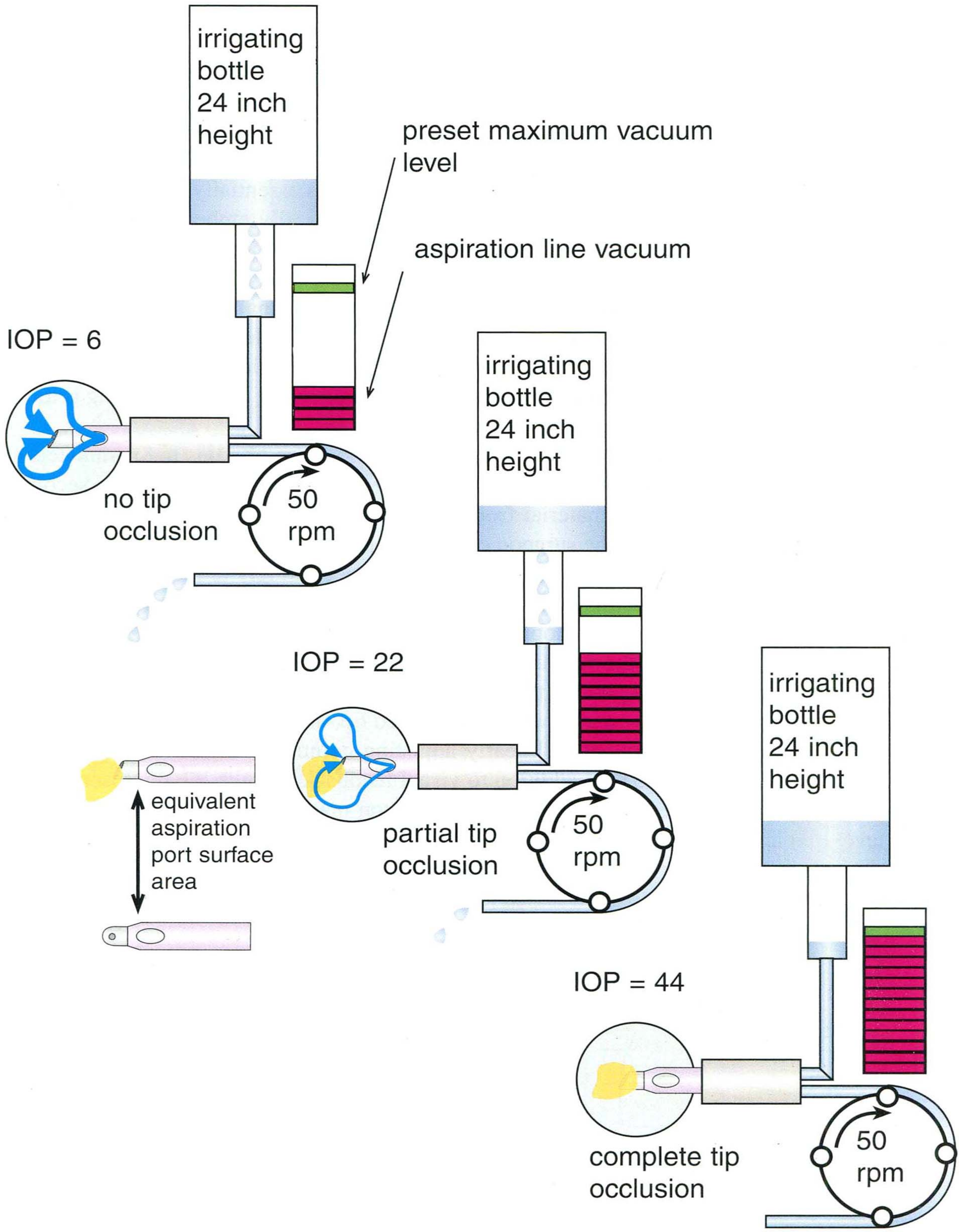

irrigating bottle 24 inch height
preset maximum vacuum level
aspiration line vacuum
IOP = 6
no tip occlusion
50 rpm
irrigating bottle 24 inch height
IOP = 22
partial tip occlusion
50 rpm
equivalent aspiration port surface area
irrigating bottle 24 inch height
IOP = 44
complete tip occlusion
50 rpm

FIGURE 1-11

Flow Pumps: Direct Vacuum Control with Tip Occlusion

As discussed with Figure 1-8, a flow pump's vacuum limit setting does not typically produce that commanded level of vacuum in the aspiration line if the aspiration port is not occluded. However, once the vacuum limit is reached after a tip occlusion, such as with the bottom diagram in Figure 1-11 or either diagram in Figure 1-12, the surgeon does essentially have control of commanded vacuum. For example, the phaco tip has been ultrasonically embedded into the nuclear fragment with position 3, and the pedal is then relaxed into the bottom of position 2 in order to achieve the full level of the vacuum limit (green bar in Figure 1-12-1). Note how the pump head on this machine is only intermittently moving forward (multiple small curved arrows on pump head) to augment venting in order to keep the vacuum from building past the preset limit. However, the surgeon may note at this level that the nuclear particle is intermittently and irregularly partially aspirating into the tip, indicating that the vacuum level at this limit setting is too high to achieve a stable grip with this particular nuclear density.

Recall the discussion with Figure 1-4 stressing the importance of adjusting parameters such that pedal position 2 can serve the clinical goal of gripping while position 3 provides a second and independent function of aspirating material from the eye. Assuming that this machine has linear control of vacuum in phaco mode, the surgeon can lift the pedal into the midway position of position 2 (Figure 1-12-2), lowering the aspiration line vacuum accordingly to a level more appropriate for gripping and manipulating this nuclear particle in a stable manner without premature irregular aspiration (eg, in preparation for chopping); note the pump head slightly reversing direction (dashed curved arrow) to lower the vacuum as commanded by the slightly raised foot pedal, an advanced design currently employed on the latest machines from Bausch & Lomb, Alcon, and AMO. This commanded vacuum control with an occluded tip, and a flow pump with linear vacuum control, is the clinical equivalent of linearly adjusting commanded vacuum with a vacuum pump, such as seen in Figure 1-31. In addition to visual feedback through the microscope as well as proprioceptive feedback from the foot pedal, the surgeon may also judge how the commanded vacuum level is being changed by **audible feedback** featured on most machines, whereby the vacuum level is typically proportional to the pitch of the tone (ie, higher pitch indicating higher vacuum level).

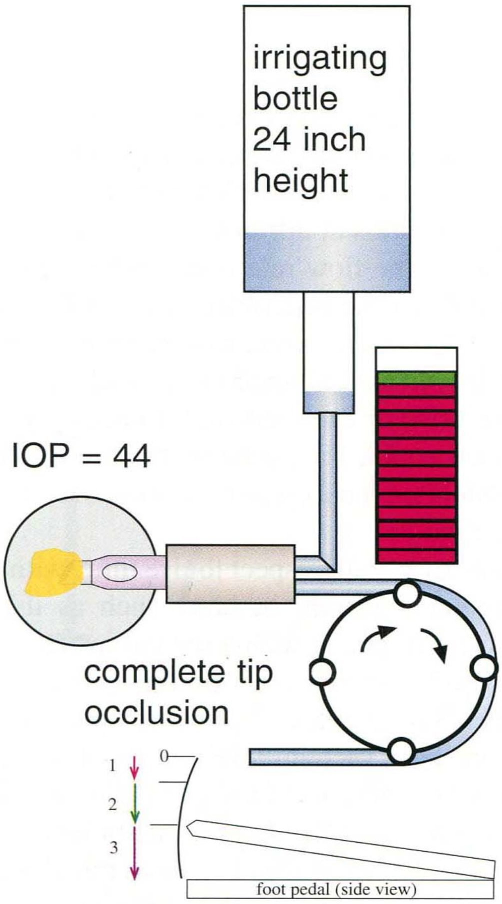


Figure 1-12-1

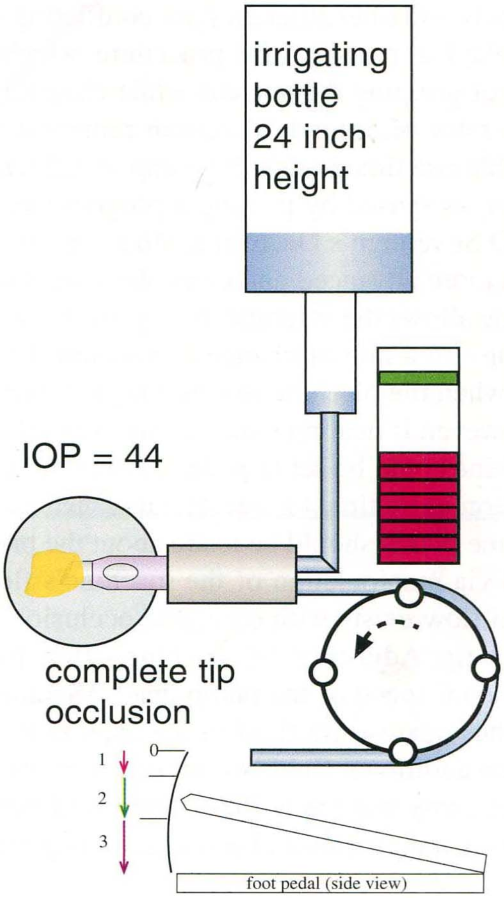


Figure 1-12-2

FIGURE 1-12

Rise Time: Flow Pumps

Rise time is inversely proportional to the rotational speed of the pump head (Figure 1-13). All graphs represent the same hypothetical phaco machine with an occluded aspiration port and a preset vacuum limit of 400 mm Hg. At time zero, the pedal is abruptly pressed into the bottom of position 2. The different plots represent how vacuum builds at different rates when this particular machine is set to different flow rates. Note that when the flow rate is cut in half (from 40 to 20 cc/min), the rise time is doubled (from 1 to 2 sec). Rise time is doubled again to 4 sec when flow rate is halved again to 10 cc/min. A longer rise time gives the surgeon more time to react in cases of inadvertent incarceration of iris, capsule, or other unwanted material; in such cases, the pedal can be raised to position 1 (for venting; see Figure 1-15) or even refluxed if necessary before dangerously high levels of vacuum are reached, which could, for example, rupture an incarcerated capsule. Although a useful setting for training residents, even experienced surgeons appreciate the enhanced safety margin afforded by a longer rise time.

Safety and time efficiency are conflicting objectives with respect to rise time, with longer rise times delaying parts of the procedure which require vacuum buildup, such as thick cortical removal or gripping the nucleus while chopping off a fragment with a second instrument; moderate flow rates of around 30 cc/min represent a good compromise. Some machines offer a programmable rise time in that the pump speed can be set to increase or decrease upon aspiration port occlusion, as sensed by passing a programmed threshold vacuum level; examples of this include the AMO Sovereign's Occlusion Mode Phaco as well as Surgical Design's Adjustable Rise Time. An even more advanced and clinically useful algorithm is utilized in the Alcon Infiniti; Dynamic Rise Time allows the machine to vary rise time according to not simply a fixed threshold but rather in response to a rate of change of vacuum. For example, a surgeon could elect to have rise time shorten when the machine senses a rapidly increasing vacuum level that would indicate an occlusion. However, if dealing with a compromised environment such as a small pupil or weak zonules, the machine could be set to instead lower the rise time when sensing an occlusion, thereby giving the surgeon more time to react in unwanted material is aspirated.

Some points should be made about the preceding discussion on rise time. First, rise time was adjusted via manipulation of the machine's flow rate control. However, as discussed previously, no actual flow exists with complete occlusion, which is necessary to efficiently build vacuum at the phaco tip. Adjusting the machine's flow parameter, measured in cc/min, actually determines the rotational speed of the pump head. Vacuum builds more quickly as the pump head more rapidly pushes against the fluid in the aspiration line tubing (peristaltic) and cassette (scroll), even though no additional fluid is removed from the anterior chamber through the occluded phaco tip. However, a tiny volume of fluid is removed from the aspiration line between the occlusion and the pump as vacuum builds and compliance is pulled out of the system (see Figures 1-47 and 1-48-1).

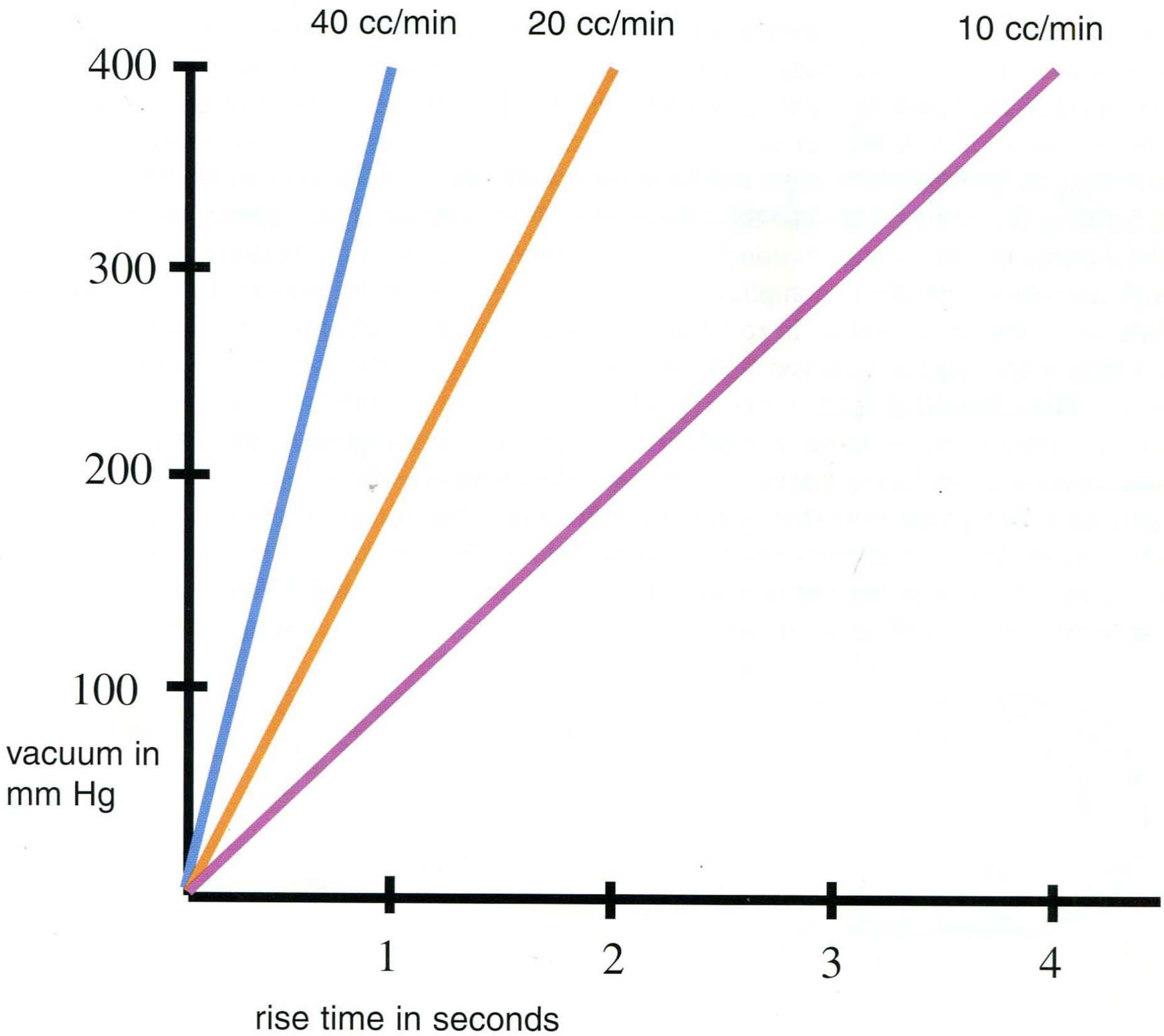

40 cc/min
20 cc/min
10 cc/min
400
300
200
100
vacuum in
mm Hg
1
2
3
4
rise time in seconds

FIGURE 1-13

Rise Time: Flow Pump Compliance

Another point regarding the rise time discussion concerns the fact that although no fluid flows from the eye with tip occlusion, a minute amount of fluid is pumped from the aspiration line tubing as vacuum is built up, thus accounting for the relation of pump speed to rise time. Because fluid is noncompressible and nonexpansile, theoretically no change in aspiration line fluid volume would occur as the pump head exerted pressure on the fluid. However, two factors account for this not being true with peristaltic pumps. First, the use of the aspiration line tubing as a conduit for transmitting the pump rollers' force results in some volumetric inefficiency in the form of leakage both between the pump rollers and the tubing, as well as in between the opposed internal surfaces of the aspiration line tubing. Second, the mechanism of action of a peristaltic pump requires enough aspiration line tubing compliance to allow for collapse by the pump rollers. **Compliance**, defined as a change in volume in response to a change in pressure, results in some tubing constriction as some fluid is removed from the aspiration line (not the eye) by the pump even with complete tip occlusion (Figure 1-14). Higher compliance in a fluidic circuit generally results in longer rise times as the pump has to work first to overcome the compliance before working to build vacuum against an occluding fragment at the aspiration port (see also Figure 1-46). The most modern peristaltic pumps minimize the system's compliance to the minimum level compatible with the functioning of the pump, thereby attaining fairly rapid potential rise times. Examples, as discussed with Figure 1-9, include bicompliant aspiration line tubing (Alcon and AMO), software compensation for volumetric efficiency (Bausch and Lomb), and Alcon's Fluid Management System.

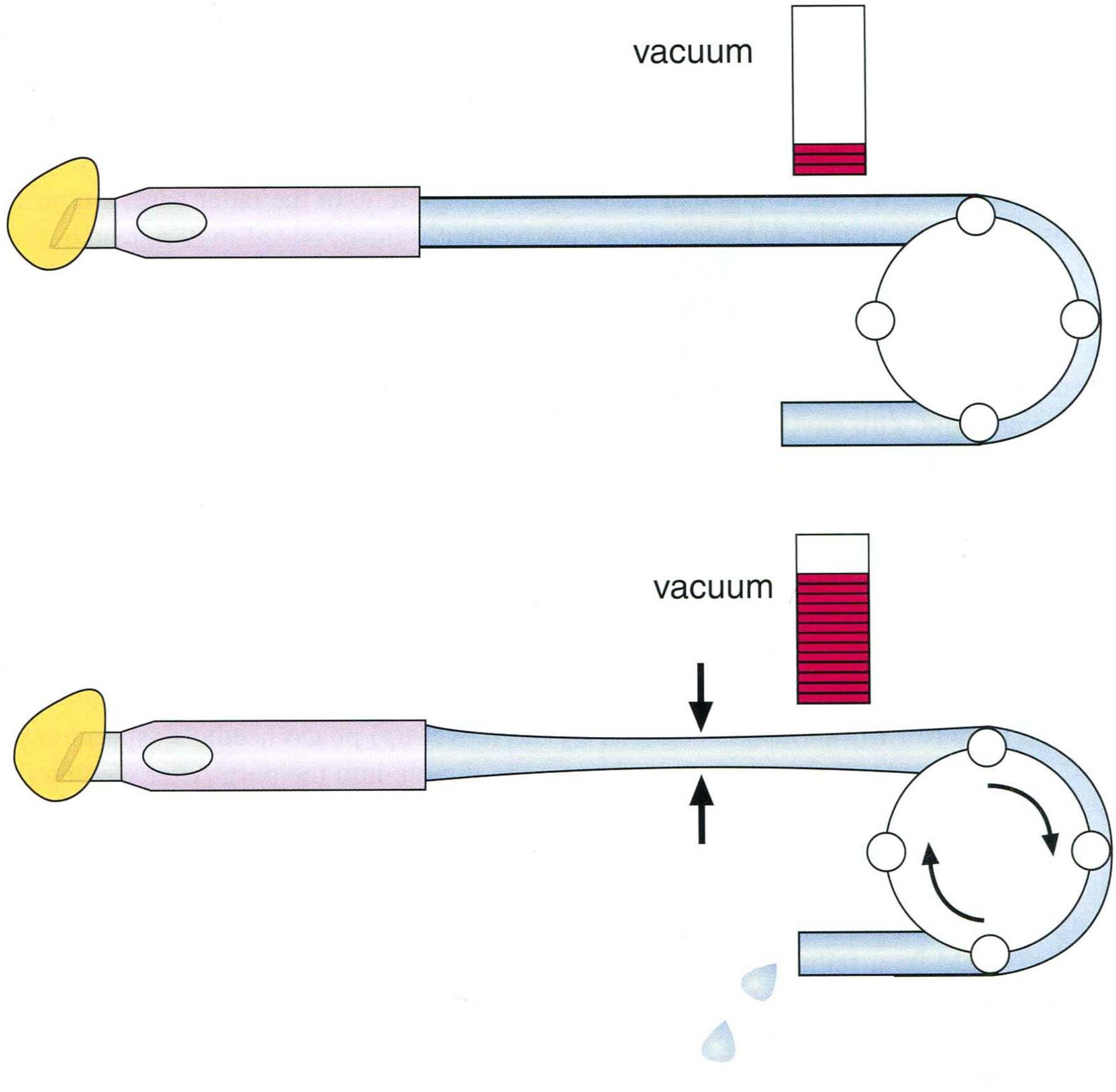


FIGURE 1-14

Rise Time: Flow Pump Venting and Vacuum Limit Preset

The final point concerning rise time and flow pumps is the fact that a maximum vacuum limit can be preset on the machine. In order to prevent vacuum buildup past this level, a variety of methods are employed. For example, the pump head can be stopped when the preset value is reached; some newer machines progressively decrease the pump speed as the vacuum limit is approached. Alternatively, or additionally, vacuum can be regulated with a moving pump head by venting air or fluid into the aspiration line if the preset value is exceeded. Venting is also employed if the surgeon wishes to reduce the vacuum either partially or completely. In the latter case, a typical clinical purpose would be to release material (eg, inadvertently incarcerated material such as iris or capsule) which is held to the phaco tip with vacuum; in this case, venting is engaged automatically on most modern phaco machines (both flow and vacuum pumps) by simply raising the foot pedal out of position 2 and into position 1 or 0. Figure 1-15-1 illustrates a nuclear fragment firmly gripped by the phaco tip with high vacuum, whereas Figure 1-15-2 shows the fragment still in position but not held with any force after the air from the vent valve purged the trapped vacuum; the fragment could be easily removed at this point with either a second instrument or with reflux. Air venting has the disadvantage of increasing the fluidic circuit's compliance relative to fluid venting. Higher compliance increases rise time and decreases the machine's responsiveness to foot pedal vacuum control (see Figure 1-46). By employing either air or fluid venting to regulate vacuum buildup, a flow pump therefore directly controls flow but also allows indirect control of vacuum.

One way to evaluate a machine's venting performance is to utilize a porcine wet lab. The contra-incisional posterior iris surface is engaged by the (bevel-up) phaco needle's aspiration port in position 2 while the anterior iris surface is observed to dimple into the port. After waiting for rise time to build to the vacuum preset limit (eg, 100 to 200 mm Hg), the pedal is then raised into position 1 (recall that position 1 is reached by raising the pedal completely if continuous irrigation mode is engaged). Ideally, the surgeon should observe an immediate gentle release of the incarcerated iris as the anterior surface resumes its normal flat architecture. Examples of poor venting performance would be a failure to release the iris (eg, anterior dimple does not flatten out), an overly forceful release of the iris (eg, the anterior iris surface momentarily bulges anteriorly upon release), or an immediate regrabbing of the iris after a momentary release (ie, reformation of the anterior iris dimple after a momentary flattening).

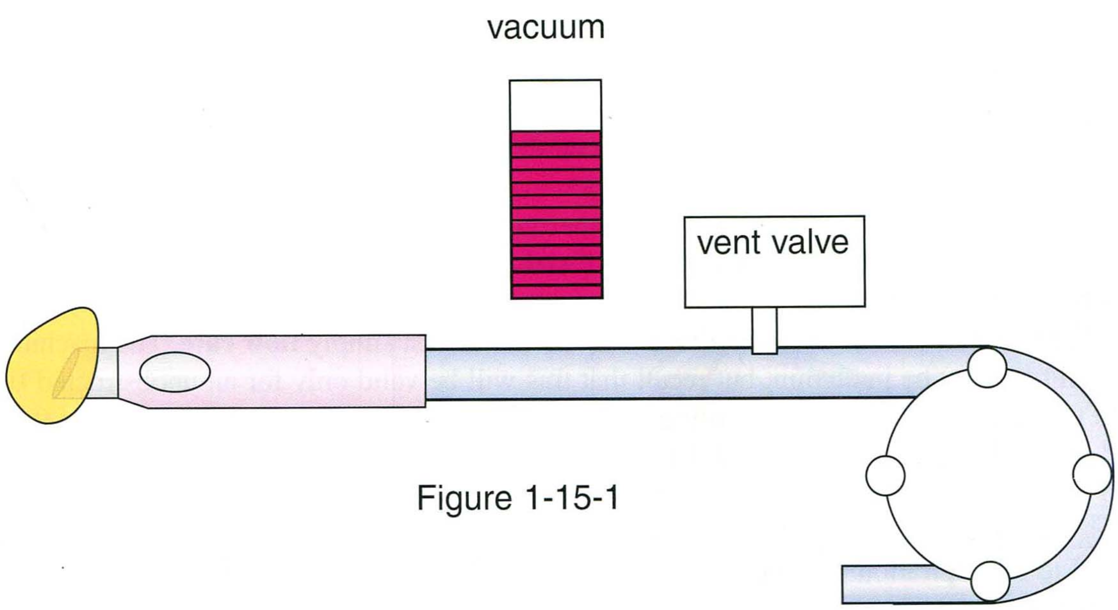


Figure 1-15-1

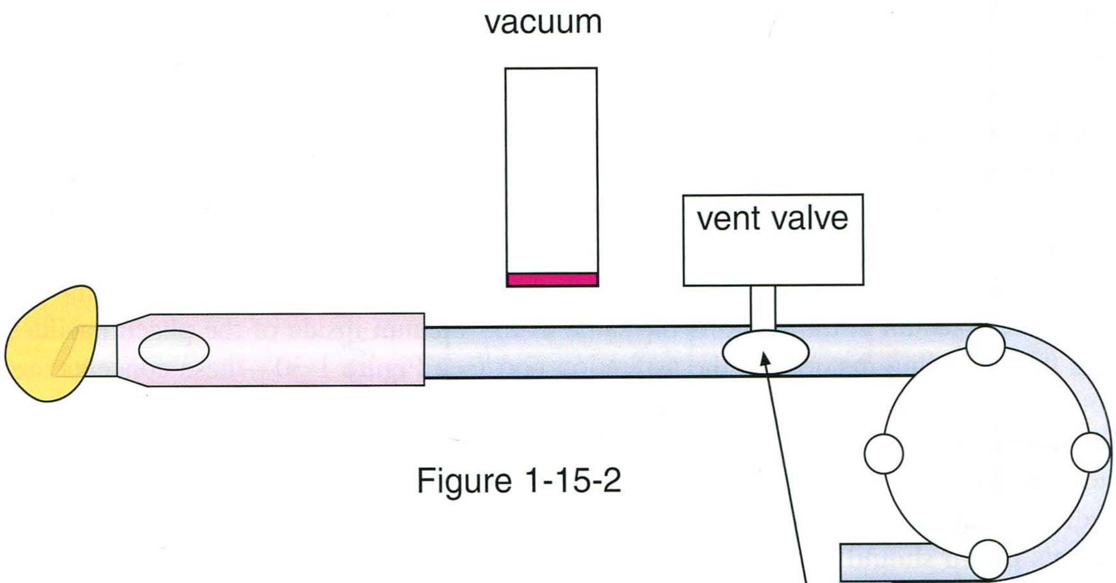


Figure 1-15-2

FIGURE 1-15

Schematic Machine: Flow Pump

The original schematic from Figure 1-1 will now be enhanced in order to expand on the previously discussed concepts regarding rise time; for simplicity, the **pressure transducer** is assumed to be within the pump housing between the aspiration line inlet and the pump head; it is shown with dashed lines here but will be hidden in subsequent drawings. The transducer enables fluid dynamic modeling of the eye so that control inputs are accurately achieved and anterior chamber stability is enhanced. A Dual Linear Pedal is seen in side view. Note the new displays on this schematic (Figure 1-16).

Pump flow is also know as **aspiration flow rate** or just simply **flow rate**. The machine display will typically be in cc/min, but recall that this will be valid only for an unobstructed fluidic circuit (see Figure 1-11). When adjusting this parameter, the surgeon is actually adjusting the rotational speed of the pump head, and if the aspiration port is occluded, then increasing the pump speed will decrease rise time (see Figure 1-13). Increasing the flow rate with an unobstructed tip will produce stronger and more rapid anterior chamber currents which will more readily attract material to the aspiration port, such as nuclear fragments and cortex, as well as iris and capsule.

The **maximum vacuum limit**, measured in mm Hg, is preset by the surgeon. It represents the highest vacuum obtainable given complete occlusion of the aspiration port. Without this limiting set point, a rotating flow pump would continue to build vacuum to dangerous levels. Once again, the speed with which this level is reached (the rise time) is proportionately determined by the flow rate setting.

Actual vacuum indicates the real-time vacuum pressure at the machine's pressure transducer, which is usually located at or within the pump housing. With an unoccluded tip and an operating pump (pedal position 2 or 3), vacuum decays (ie, pressure becomes more positive) in the fluidic circuit from the pump toward the anterior chamber (see Figure 1-32 for a flow pump; see also Figure 1-42 for the same principle illustrated with a vacuum pump); however, with an occluded tip, the actual vacuum at the pump is the same as the vacuum inside of the phaco needle that is holding the occluding material to the aspiration port (see Figure 1-30—these concepts are valid for both flow and vacuum pumps). The actual vacuum is a percentage of the maximum vacuum up to 100%; variables that influence it include the maximum vacuum preset, the pump flow, the size of the aspiration port, the length and internal diameter of the aspiration line tubing, the degree of tip occlusion, and the position of the foot pedal when linear control is used. **Note that the machine's pump should be placed at the patient's eye level to standardize not only the vacuum transducer readings, but also the amount of irrigating bottle elevation**.

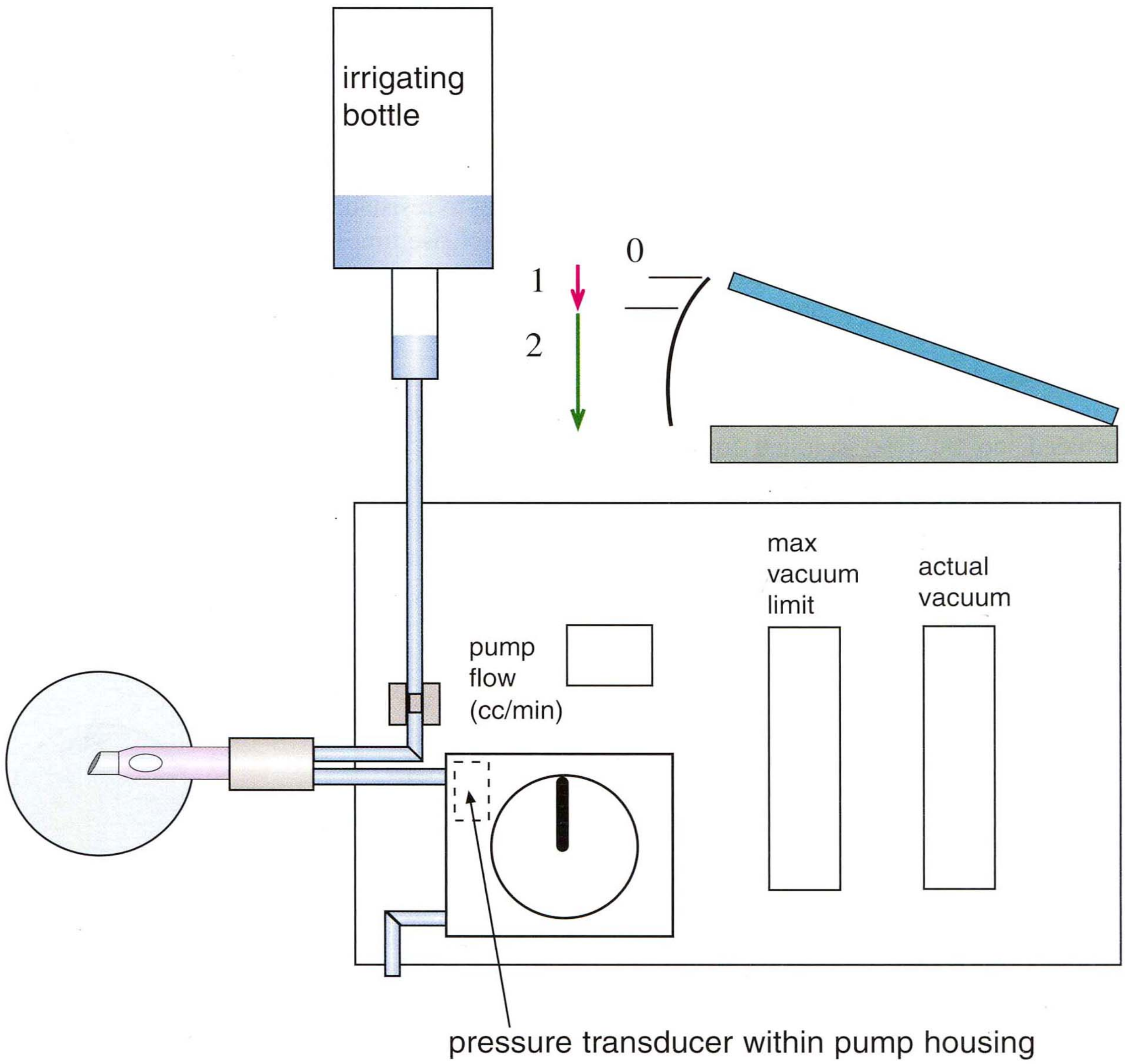

irrigating
bottle
0
1
2
max
vacuum
limit
actual
vacuum
pump
flow
(cc/min)
pressure transducer within pump housing

FIGURE 1-16

Relationship Among Flow Rate, Rise Time, and Vacuum

The following schematics illustrate how increasing the flow rate decreases rise time (see Figure 1-13). The time displays utilize zero as the time when the tip is already completely occluded with the nuclear fragment, and pump action is initiated by abruptly pushing the foot pedal from position 0 to the bottom of position 2 (note that the pedal is in IA mode; see Figure 1-4). Because the pump starts right at time zero with complete occlusion of the aspiration port, the following schematics do not demonstrate any vacuum preload due to resistance to flow at higher flow rates (see Figure 1-10A). Therefore, the mechanism of shorter rise times with faster flow rate settings is due to the more rapid rotational speed of the pump head more rapidly driving the aspiration line fluid and thus building vacuum more quickly. For these illustrations, the maximum vacuum limit has been set to 400 mm Hg.

Figure 1-17: **20 cc/min pump flow. Time: 0.1 sec.** At this instant just after complete occlusion, actual vacuum has not had a chance to build yet. However, because the tip is completely occluded, no fluid is aspirated from the eye (note the lack of drainage from the machine). Consequently, because of the sealed anterior chamber, irrigation also ceases (note the lack of activity in the drip chamber).

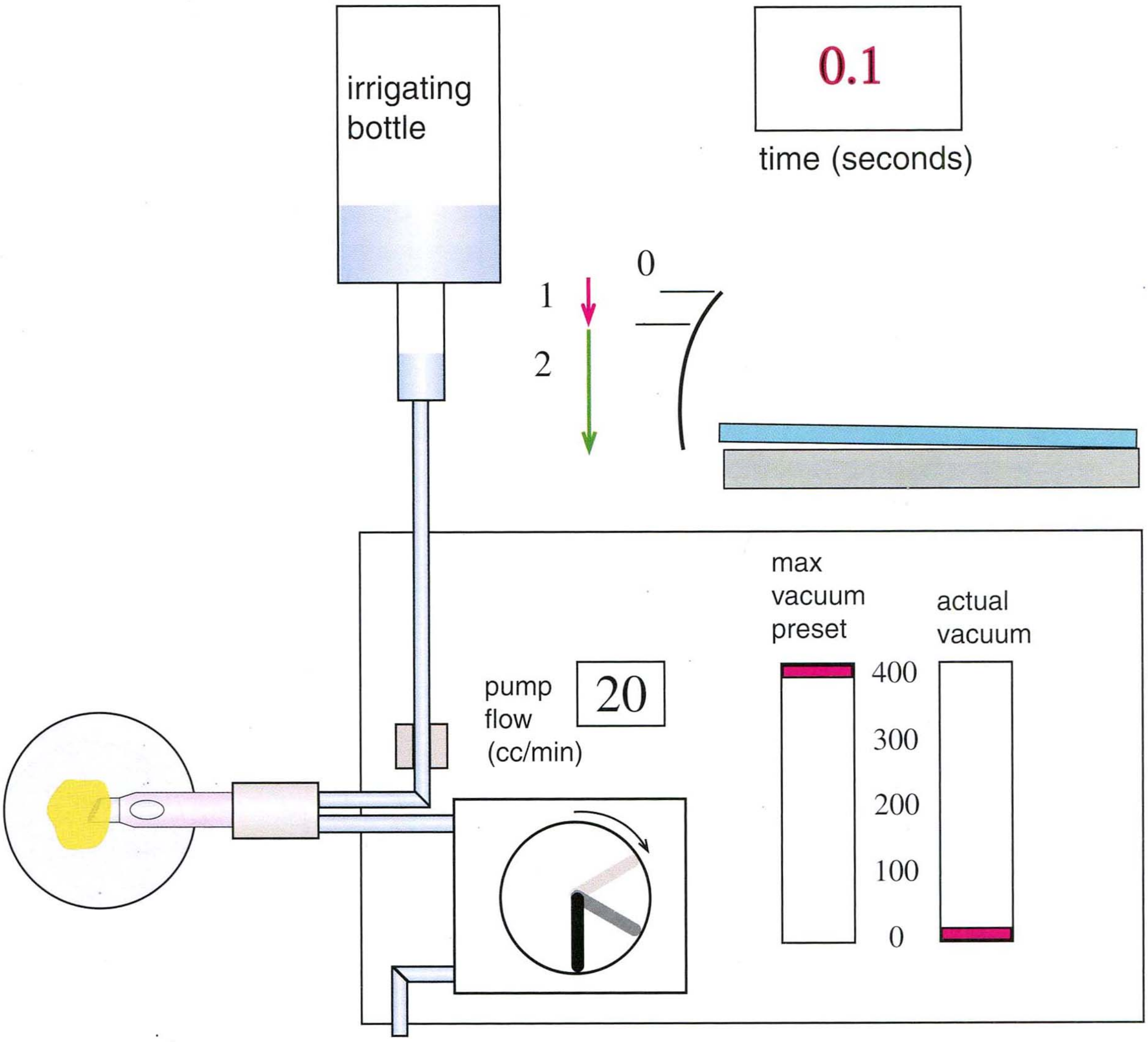

irrigating
bottle
0.1
time (seconds)
0
1
2
max
vacuum
preset
actual
vacuum
pump
flow
(cc/min)
20
400
300
200
100
0

FIGURE 1-17

Relationship Among Flow Rate, Rise Time, and Vacuum (continued)

Figure 1-18: **20 cc/min pump flow. Time: 2 sec.** As the pump head continues to drive infinitesimally small amounts of fluid through the aspiration tubing, actual vacuum begins to rise. After 2 sec, it has reached a level of 200 mm Hg on this particular machine. As the pump is building vacuum, it is overcoming any fluidic circuit compliance (see Figures 1-14, 1-46, and 1-47).

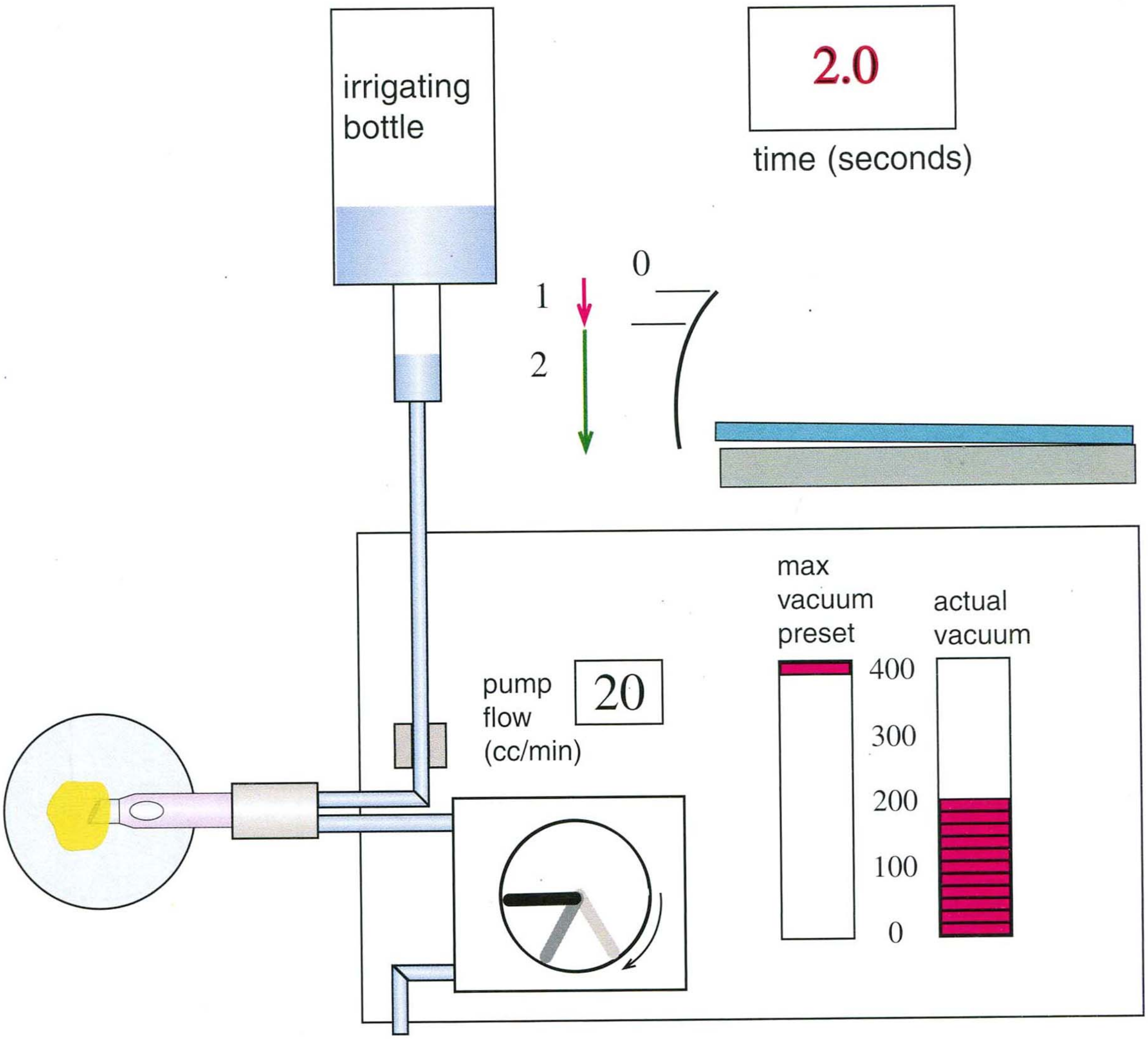

irrigating bottle
2.0
time (seconds)
0
1
2
max vacuum preset
actual vacuum
400
300
200
100
0
pump flow (cc/min)
20

FIGURE 1-18

Relationship Among Flow Rate, Rise Time, and Vacuum (continued)

Figure 1-19: **20 cc/min pump flow. Time: 4 sec**. The actual vacuum has now reached the maximum preset limit value of 400 mm Hg.

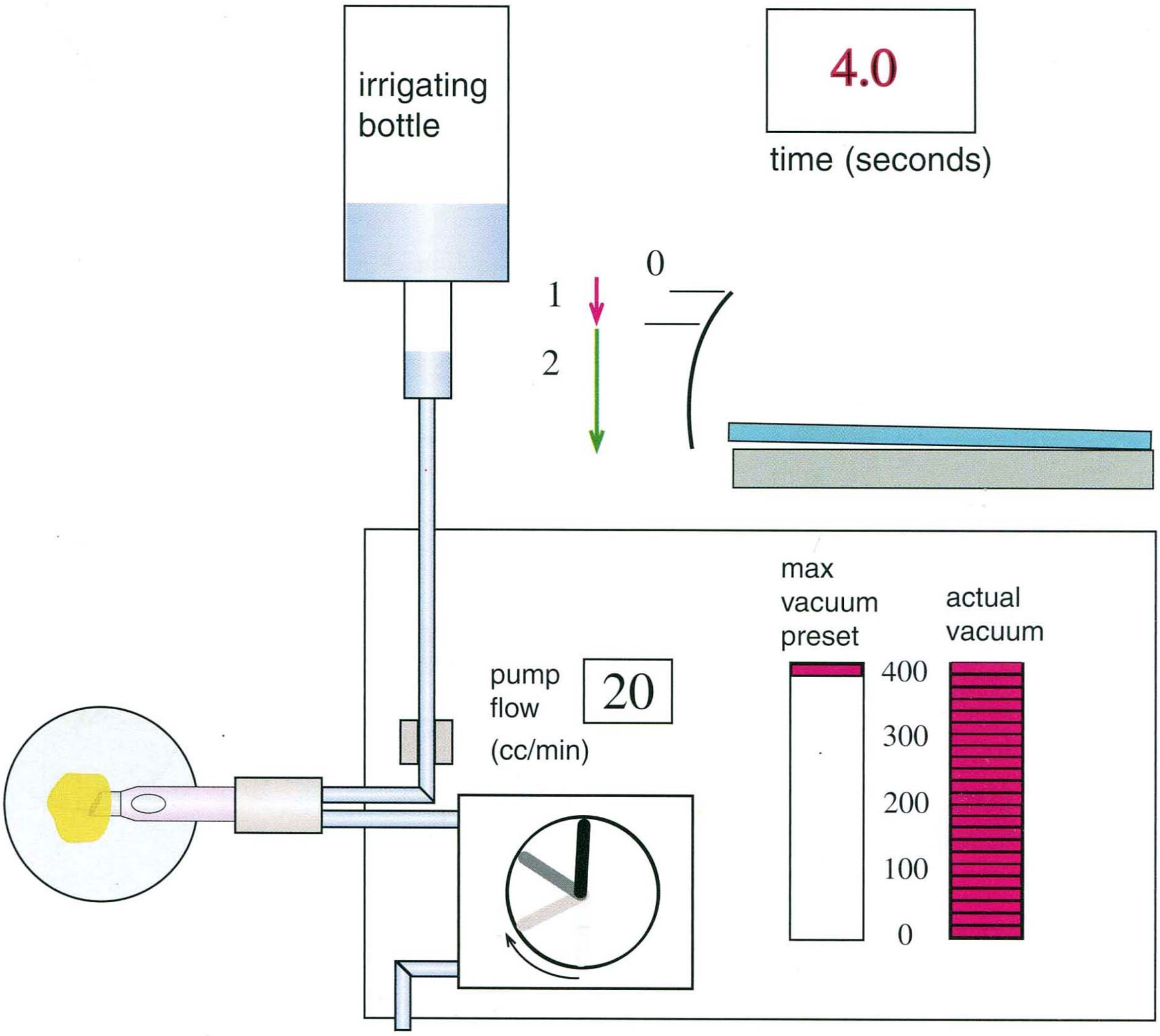
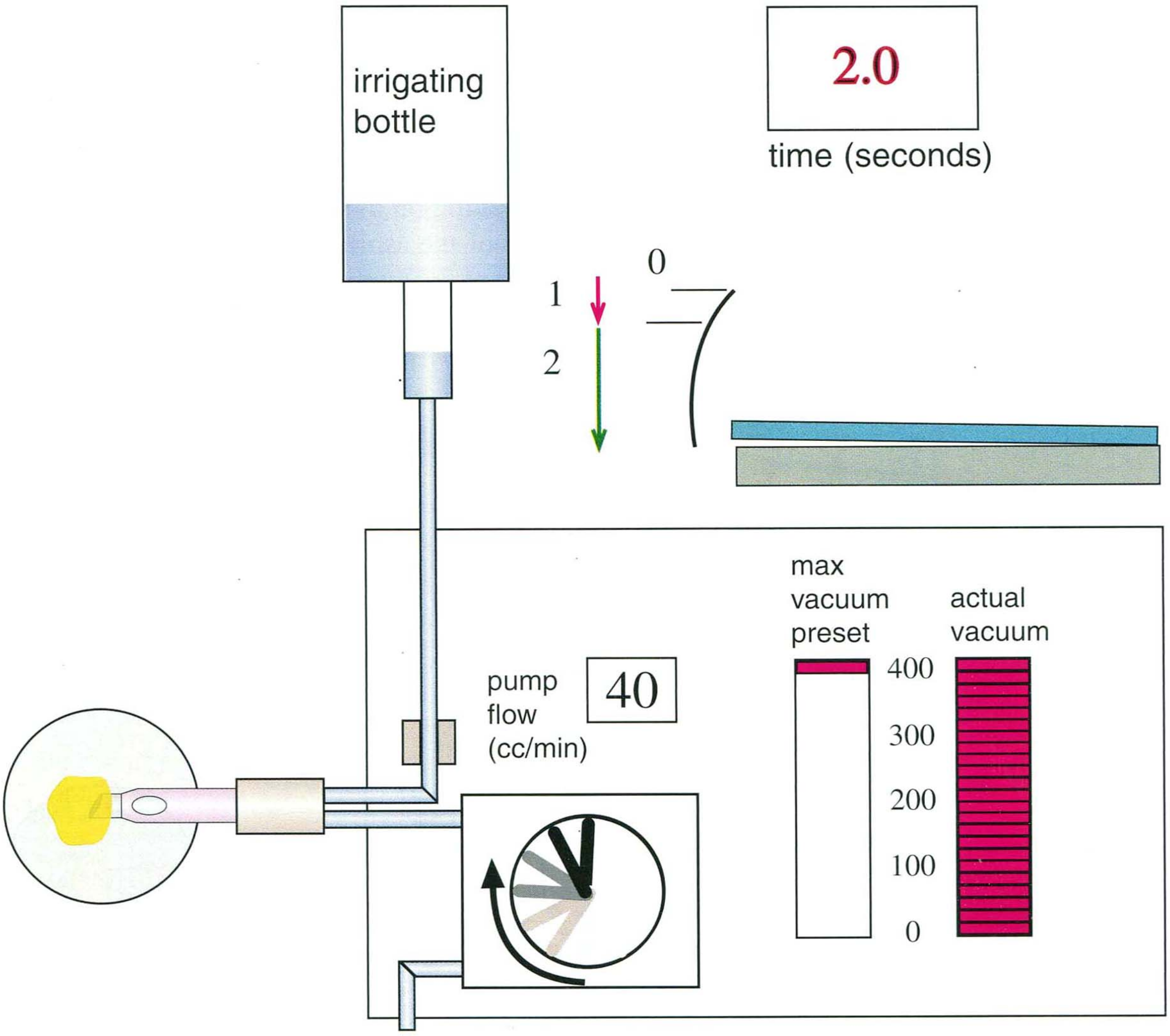

irrigating
bottle
4.0
time (seconds)
0
1
2
max
vacuum
preset
actual
vacuum
pump
flow
(cc/min)
20
400
300
200
100
0

FIGURE 1-19

Relationship Among Flow Rate, Rise Time, and Vacuum (continued)

Figure 1-20: **40 cc/min pump flow. Time: 2 sec**. For this illustration, the machine had been reset to 40 cc/min flow; at time zero, the tip was completely occluded, the actual vacuum was zero, and the foot pedal was abruptly depressed from position 0 to the bottom of position 2. By doubling the pump flow (therefore doubling the rotational speed of the pump head), the time required to reach the maximum vacuum (ie, rise time) has been cut in half (compare to Figure 1-19). At 40 cc/min flow rate on this particular machine, vacuum rises at a rate of 100 mm Hg every 0.5 sec.



irrigating bottle
2.0
time (seconds)
0
1
2
max vacuum preset
actual vacuum
pump flow (cc/min)
40
400
300
200
100
0

FIGURE 1-20

Relationship Among Flow Rate, Rise Time, and Vacuum (continued)

Figure 1-21: **40 cc/min pump flow. Time: 2 sec**. The machine has again been reset for this illustration. Time zero begins with complete tip occlusion, zero vacuum, and the foot pedal being abruptly depressed from position 0 to a point halfway into position 2, which on this particular linear control machine yields a maximum potential vacuum of half of the maximum preset vacuum (ie, 200 mm Hg). Although the time reading is 2 sec, the actual vacuum of 200 mm Hg was reached after 1 sec. Recall that a 40 cc/min pump flow setting on this particular machine increases vacuum by 100 mm Hg every 0.5 sec with occlusion of the aspiration port (see Figure 1-20). Between the time readings of 1 and 2 sec, this machine was venting (see Figure 1-15), a combination of intermittent pump cessation coupled with air (or fluid) introduction into the aspiration line which serves to prevent the actual vacuum from increasing past 200 mm Hg as determined by the combination of linear pedal position and the maximum vacuum preset.

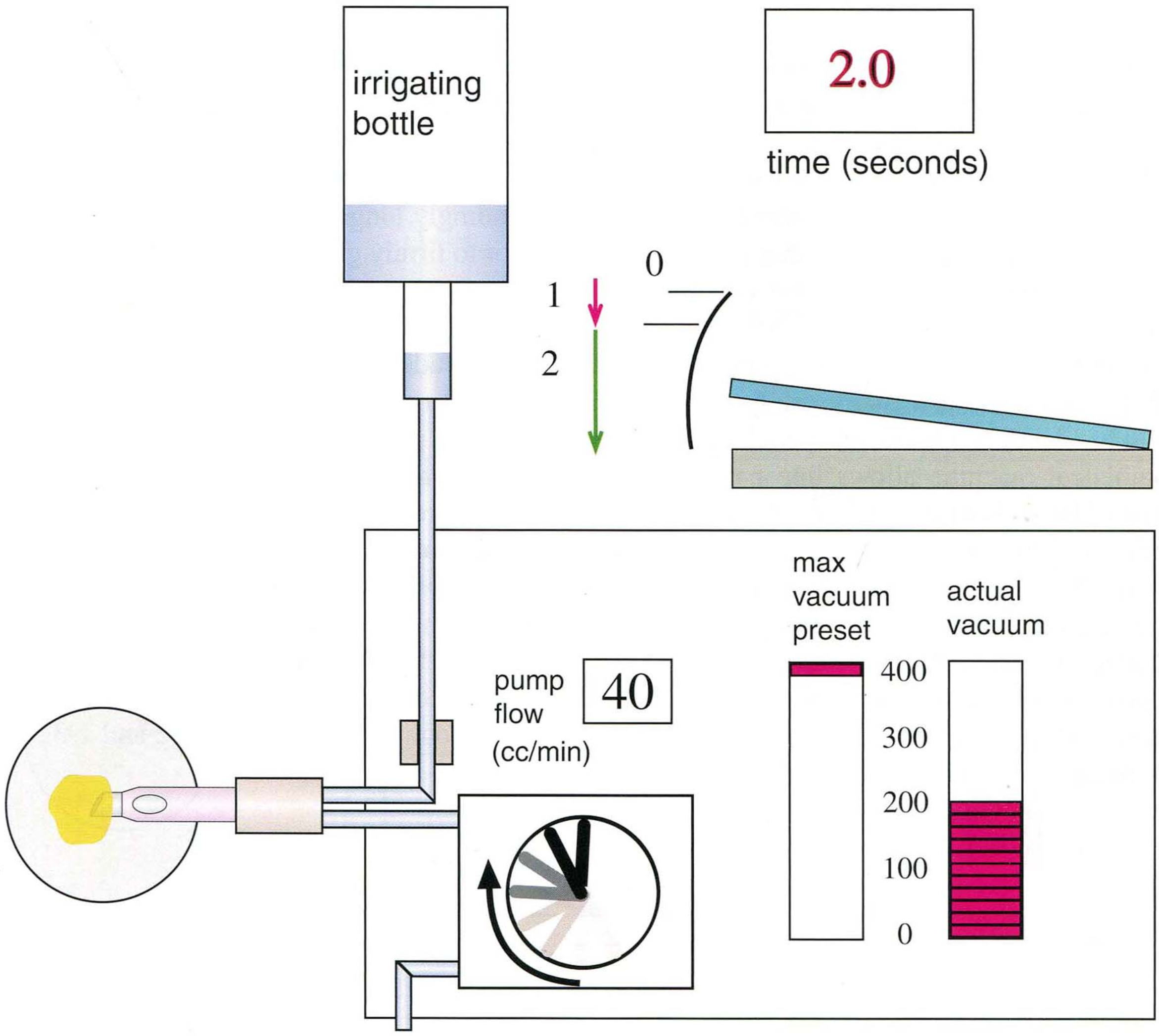
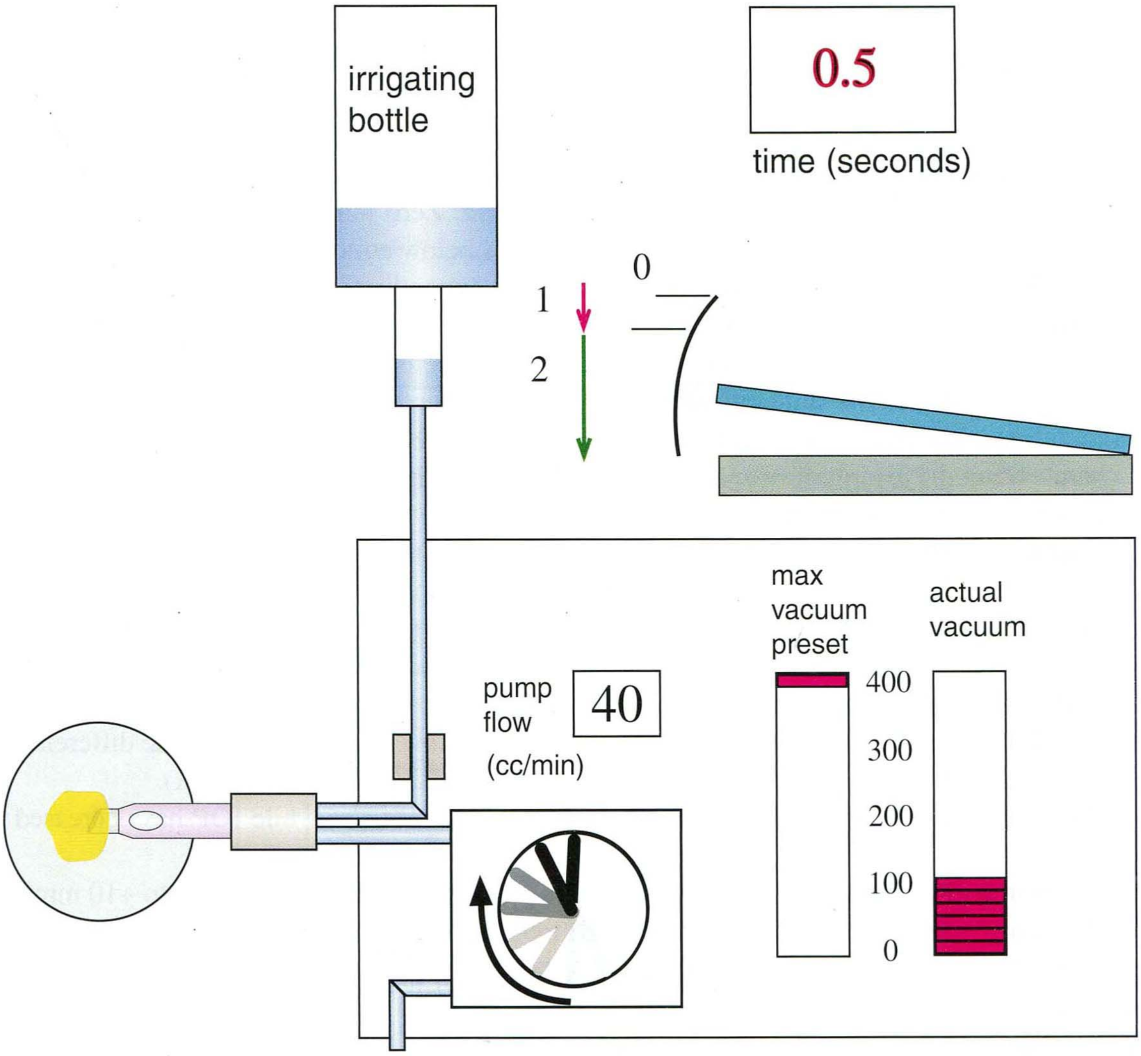

irrigating bottle
2.0
time (seconds)
0
1
2
max vacuum preset
actual vacuum
pump flow (cc/min)
40
400
300
200
100
0

FIGURE 1-21

Relationship Among Flow Rate, Rise Time, and Vacuum (continued)

Figure 1-22: **40 cc/min pump flow. Time: 0.5 sec**. Again, the machine has been reset so that time zero begins with complete occlusion, zero vacuum, and the pedal being abruptly depressed from position 0 to a point halfway into position 2's travel. With a maximum vacuum preset limit of 400 mm Hg and the linear control pedal halfway into position 2, the **maximum potential vacuum (MPV)** is 200 mm Hg. However, after just 0.5 sec, the actual vacuum is only 100 mm Hg (recall that a 40 cc/min flow setting yields a rise time rate of 100 mm Hg/0.5 sec on this machine—see Figure 1-20). Remember this **rise time lag** when clinically evaluating vacuum level, especially when using lower flow rates which produce correspondingly longer rise times. For example, if your goal is to aspirate material that is occluding the tip or to firmly grip the nucleus prior to chopping, allow sufficient rise time for vacuum to build to the MPV before depressing the pedal still further.

Note that the rate of vacuum increase (**rise time**) is dependent only on the flow setting, which determines pump head rotational speed. The machine and time readings shown in Figure 1-22 would be identical whether the pedal was halfway or fully into position 2 because the pedal on this hypothetical machine allows linear control of vacuum, not flow. Some machines do offer the option of linear flow control, which decreases rise time by increasing flow rate (pump speed) with increased pedal depression, at the expense of having a fixed, non-linear vacuum setting. The Alcon Infiniti offers the option of both linear control of vacuum as well as linear control of flow within position 2 of phaco mode, whereby depressing the pedal farther gives more flow if the tip is not occluded, and pressing the pedal farther increases the vacuum limit (up to the preset maximum) if the phaco needle's aspiration port is occluded. This type of control, facilitated by the machine's Dynamic Rise Time feature, essentially emulates a vacuum pump (see Figures 1-12 and 1-32 for flow pumps, Figures 1-28 through 1-31 for vacuum pumps).



irrigating bottle
0.5
time (seconds)
0
1
2
max vacuum preset
actual vacuum
pump flow
(cc/min)
40
400
300
200
100
0

FIGURE 1-22

Relationship Between Flow and Vacuum 1

Figure 1-23 is measuring **IOP (intraocular pressure)** and **ALP (aspiration line pressure)** in a flow pump machine with a phaco handpiece (standard tip, no occlusion). A test chamber is placed over the phaco tip to simulate the anterior chamber, and the phaco handpiece is placed on the machine tray at the same level as the pump. The bottle height is placed 24 inches above the handpiece test chamber; this bottle height produces an IOP of 44 mm Hg hydrostatic pressure (see Appendix C). The vacuum limit is preset to 120 mm Hg. Zero mm Hg is calibrated to ambient room air atmospheric pressure; by convention, pressures below atmospheric are negative numbers (ie, -200 mm Hg pressure = +200 mm Hg vacuum, see Appendix C).

Position 1: Recall that this pedal position hydrostatically pressurizes the anterior chamber or test chamber but does not produce any actual flow or movement of fluid (Figure 1-3). There is open communication in the fluid circuit from the irrigation bottle to the test chamber (IOP) to the aspiration line to the pump (see Figure 1-1). The IOP and ALP are the same (44 mm Hg) since the test chamber and the aspiration line are on the same tray; both of them are identically pressurized by the 24-inch column of water from the irrigation bottle.

Position 2 (10 cc/min): The pump is now removing fluid from the aspiration line quickly enough to reduce the ALP to 15 mm Hg. The IOP is reduced only to 30 mm Hg because the phaco handpiece/needle combination is acting as a flow restriction (or fluidic resistor) between the test chamber and the aspiration line (see also Figure 1-41). Indeed, it is this resistance which enables the pump to build vacuum. "Vacuum" is of course a relative term and not always negative; even though both IOP and ALP are positive values in this case, flow exists because of the difference in pressure between them (see discussion of pressure differential with Figure 1-10A).

Position 2 (20 cc/min): ALP has now dropped to -20 mm Hg, while IOP has decreased to +20 mm Hg.

Position 2 (30 cc/min): ALP is down to -50 mm Hg, while IOP has dropped to +10 mm Hg.

Position 2 (40 cc/min): ALP has decreased to -90 mm Hg, while IOP hovers around 0 mm Hg. At this IOP level, the anterior chamber would be shallow and unstable; it is likely to collapse under the equivalent atmospheric pressure and especially the greater vitreous pressure. Bottle height should be increased at this flow rate in order to raise the IOP, thereby deepening and stabilizing the anterior chamber.

Note that, contrary to some previous teachings, a peristaltic (flow) pump does build vacuum without occlusion (see the negative ALPs at flow rates of 20 cc/min and greater). Even at lower flow rates, a **relative vacuum** (pressure lower than IOP) is developed in the aspiration line due to the resistance to flow from the phaco tip, as well as the aspiration line itself.

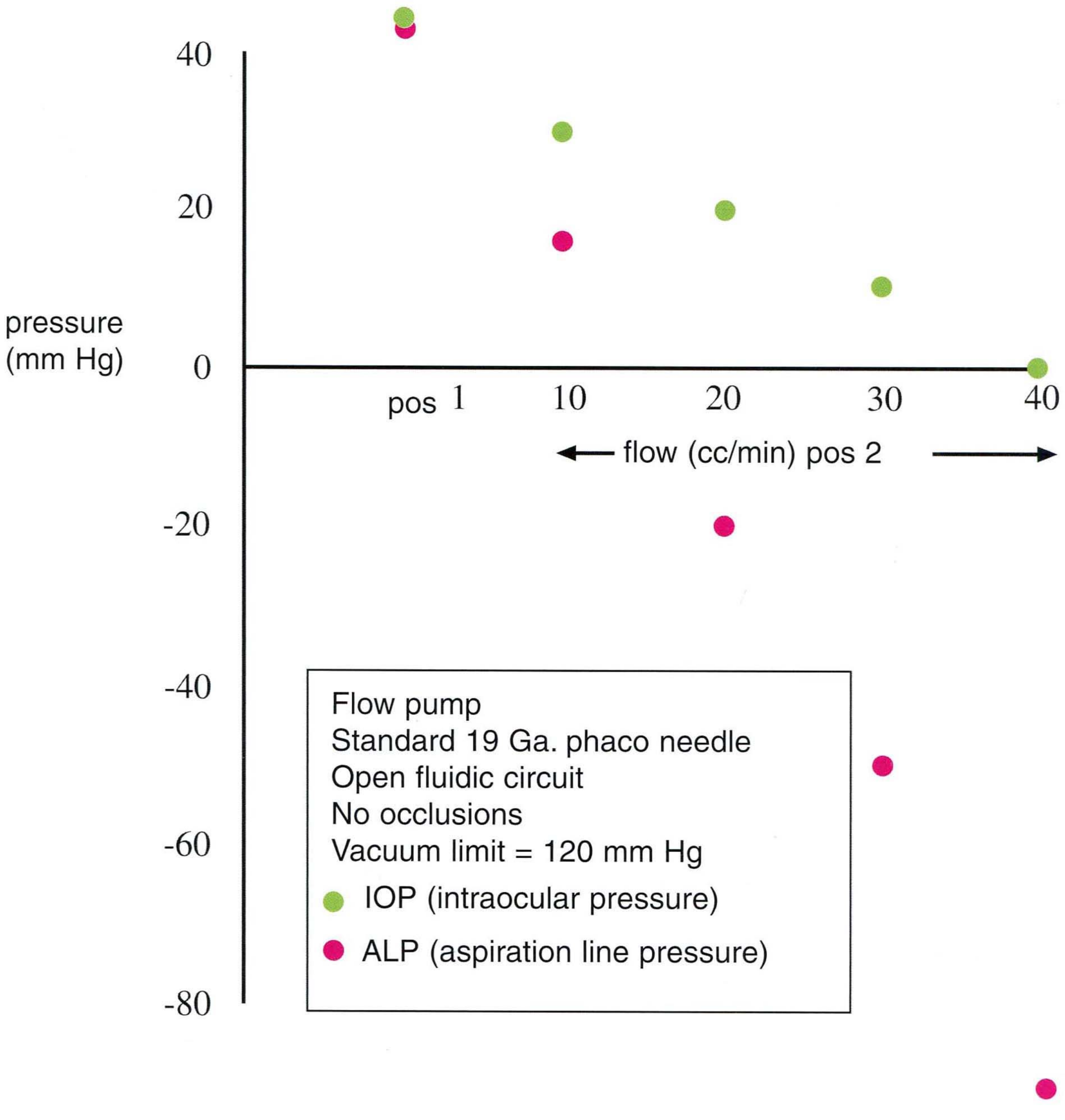

40
20
pressure
(mm Hg)
0
pos 1
10
20
30
40
flow (cc/min) pos 2
-20
-40
-60
-80
Flow pump
Standard 19 Ga. phaco needle
Open fluidic circuit
No occlusions
Vacuum limit = 120 mm Hg
IOP (intraocular pressure)
ALP (aspiration line pressure)

FIGURE 1-23

Relationship Between Flow and Vacuum 2

Position 0 (no occlusion): The irrigation pinch valve on the machine occludes the irrigation line, thereby separating the test chamber (anterior chamber) from the full pressure head of the bottle height (recall Figure 1-7). If the aspiration port in Figure 1-24 is unoccluded and is on a tray 6 inches below the machine's pinch valve, then the IOP and ALP are the result of the corresponding 6-inch column of water above the test chamber (approximately 11 mm Hg). IOP is the same as ALP because of the open communication of fluid between the test chamber and the aspiration line via the unoccluded aspiration port.

Position 1 (no occlusion): The irrigation pinch valve is open, thus allowing communication between the test chamber/aspiration line and the full 24-inch column of water between the test chamber and the irrigation bottle (the aspiration port is still unoccluded); this four-fold increase in water column height (24 vs 6 inches) produces a corresponding four-fold increase in IOP/ALP (44 mm Hg vs 11 mm Hg). This pressure differential between position 1 and 0 is readily apparent clinically whereby the anterior chamber is noted to become shallow when changing from position 1 to position 0 as a result of vitreous pressure having less opposition in position 0.

Position 2 (20 cc/min, no occlusion): ALP has dropped to -20 mm Hg, while IOP has decreased to +20 mm Hg (see also Figure 1-23).

Position 2 (20 cc/min, complete occlusion): ALP has dropped to -50 mm Hg, while IOP has increased to +44 mm Hg. Because the test chamber/anterior chamber is now isolated from the active pump by the occlusion, the IOP is simply a function of the bottle height, just as in position 1 (see above). However, with total resistance to flow, the ALP drops to the vacuum preset level (-50 mm Hg in this case). **Whether you are using a flow pump or a vacuum pump, total tip occlusion is necessary to build up holding power to the maximum preset vacuum limit (flow pump) or to the commanded vacuum level (vacuum pump)**; an important clinical example would be stabilizing the nucleus with the phaco tip while performing a phaco chop maneuver.

The effect of the tip/resistor is greater with increasing flow rates, shown schematically as increasing distance between IOP and ALP (see Figures 1-23 and 1-41). A higher resistance IA tip produces even greater pressure differentials with ALPs being lowered more and IOPs not being lowered as much relative to the phaco tip resistor. However, in unoccluded hydrostatic states without flow (positions 0 and 1), IOP is equal to ALP regardless of the tip/resistance in the fluid circuit.

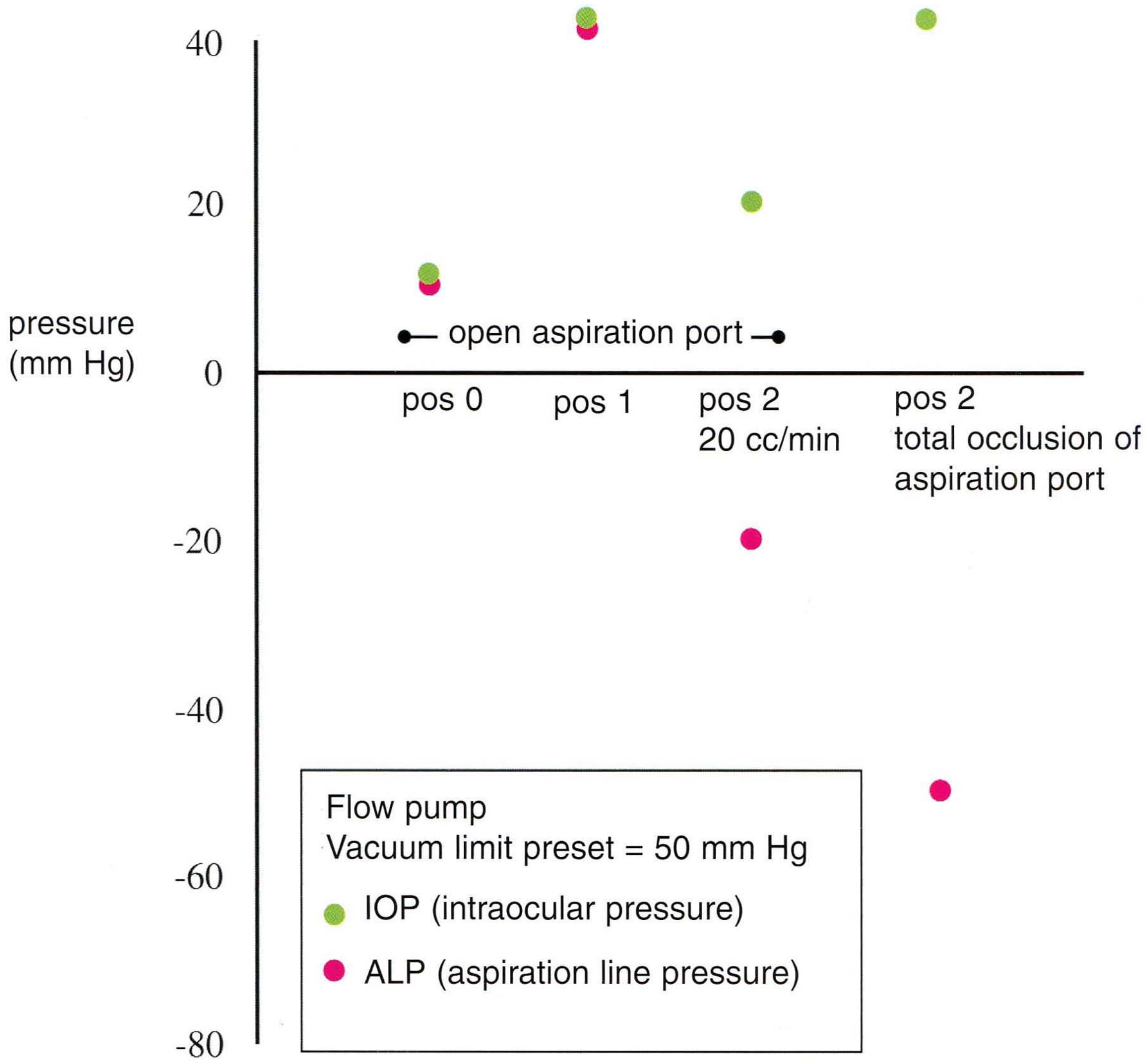

40
20
0
-20
-40
-60
-80
pressure
(mm Hg)
open aspiration port
pos 0
pos 1
pos 2
20 cc/min
pos 2
total occlusion of
aspiration port
Flow pump
Vacuum limit preset = 50 mm Hg
IOP (intraocular pressure)
ALP (aspiration line pressure)

FIGURE 1-24

Vacuum Pumps: Overview and Venturi

As opposed to a flow pump that directly controls flow as vacuum varies up to the preset limit, a vacuum pump directly controls vacuum in the fluidic circuit while it indirectly controls flow. In other words, the **surgeon commands** a given aspiration line **vacuum level**, while the flow varies according to aspiration port size and degree of occlusion, as well as according to the level of commanded vacuum and the viscosity of the aspirated fluid (Figure 1-34). Another way of differentiating the two pump types is realizing that flow pumps directly produce flow by mechanically pushing the aspiration line fluid (Figures 1-8 and 1-9) whereas vacuum pumps directly produce live vacuum within the pump that indirectly pulls on aspiration line fluid to produce flow (Figures 1-25 and 1-26). Vacuum pumps represent the second main category of phaco pumps, with examples being the rotary vane pump, the diaphragm pump, and the venturi pump.

Vacuum pumps may be differentiated from flow pumps in a number of ways. First, as already mentioned, the vacuum pump surgeon is unable to directly command a flow rate; in fact, vacuum pumps do not typically have a flow rate in cc or ml per minute anywhere on their display panel. Their only fluidic control is typically commanded vacuum in mm Hg, although this is sometimes confusingly labeled "aspiration". Second, as already mentioned, the surgeon directly commands the actual vacuum level (not just a vacuum limit) in mm Hg on a vacuum pump as opposed to commanding flow (in cc or ml per minute) on a flow pump. Third, vacuum pumps are usually indirectly linked to the fluid in the aspiration line via the air in their drainage cassette. In other words, the air in the drainage cassette is between the pump and the aspiration line, as opposed to a flow pump's rollers being directly connected to the aspiration line. Fourth, as opposed to the flexible drainage pouch employed with flow pumps, vacuum pumps must have a rigid drainage cassette or pouch that will not collapse with applied commanded vacuum from the pump; this vacuum proportionately induces flow when the aspiration port is unoccluded, thereby indirectly controlling flow by directly controlling vacuum. This indirect control of flow is particularly significant because no current vacuum pump phaco machine has an actual flow rate adjustment control; contrast this to flow pumps, which do have an independent flow rate control. Both types of pumps allow the surgeon to limit the maximum vacuum that can be achieved (flow pump) or that can be commanded (vacuum pump).

The **venturi pump** (Figure 1-25) is currently the most predominant vacuum pump; it is driven by compressed gas (nitrogen or air), which is directed through the main pump housing B. By varying the size of opening A, the volume of gas through chamber B is proportionately controlled. The gas flow over the opening of tube C into chamber B creates a pressure differential via a venturi effect with air flow as indicated by the green arrows. This air flow and pressure differential in tube C create a vacuum in the rigid drainage cassette D which pulls fluid in from the aspiration tubing in proportion to this vacuum level when the aspiration port is unoccluded. As discussed in Figure 1-31, the vacuum level in D controls the amount of grip on a fragment that occludes the aspiration port.

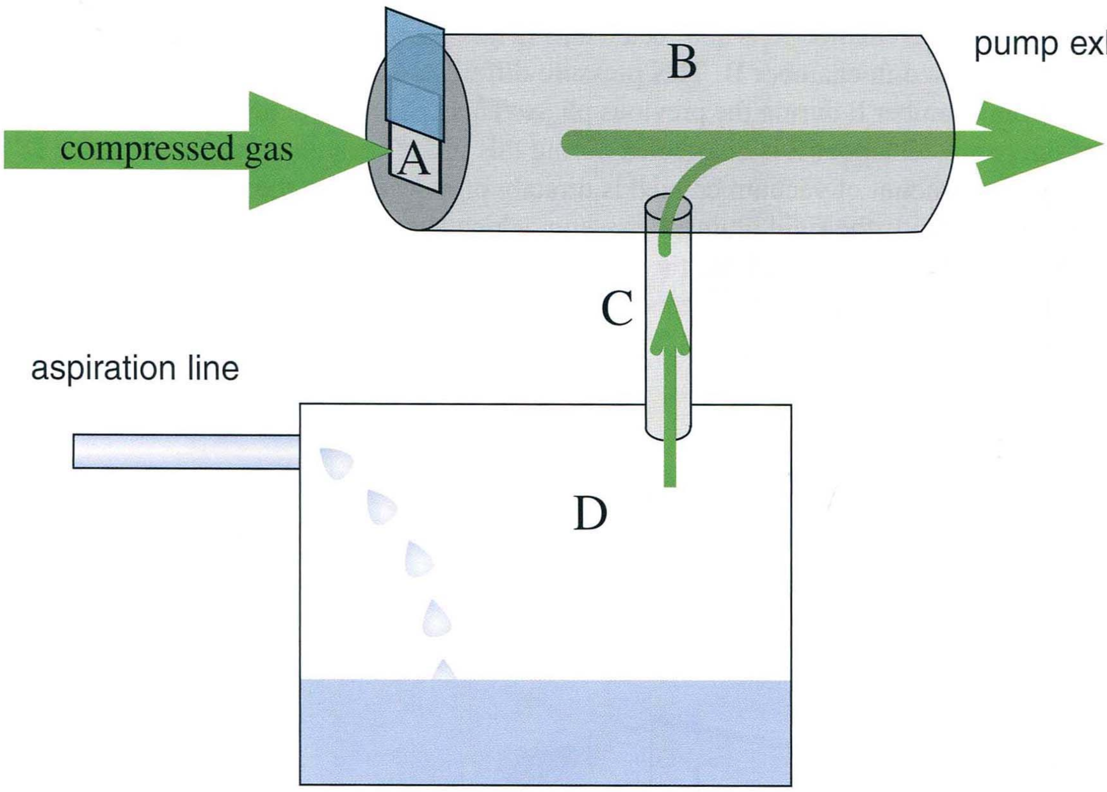


FIGURE 1-25

Diaphragm Pump

Figure 1-26 illustrates a flexible diaphragm A which is alternately pushed in and pulled out by a rod connected to an electric motor rotating as indicated. When the diaphragm is pulled out, pressure is decreased in chamber B relative to chambers E and F. This pressure differential causes valve C to open with corresponding movement of air and fluid as illustrated. Valve D cannot open into chamber B, so chamber F is unaffected during this phase. When the diaphragm is pushed in, pressure is increased in chamber B. This pressure differential opens valve D and exhausts the air pulled in from chamber E during the previous phase. This exhaust is vented into chamber F and then out of the pump. Chamber E is unaffected during this phase because valve C, like valve D, is one-way only. The amount of vacuum created is directly proportional to the pump's motor speed. For the sake of simplicity, the rigid drainage cassette, which is common to all vacuum pumps, has been incorporated into this pump schematic in the form of chamber E; in actual practice, the cassette would be linked to the pump via a tube where the aspiration line is shown, and chamber E would not have any fluid.

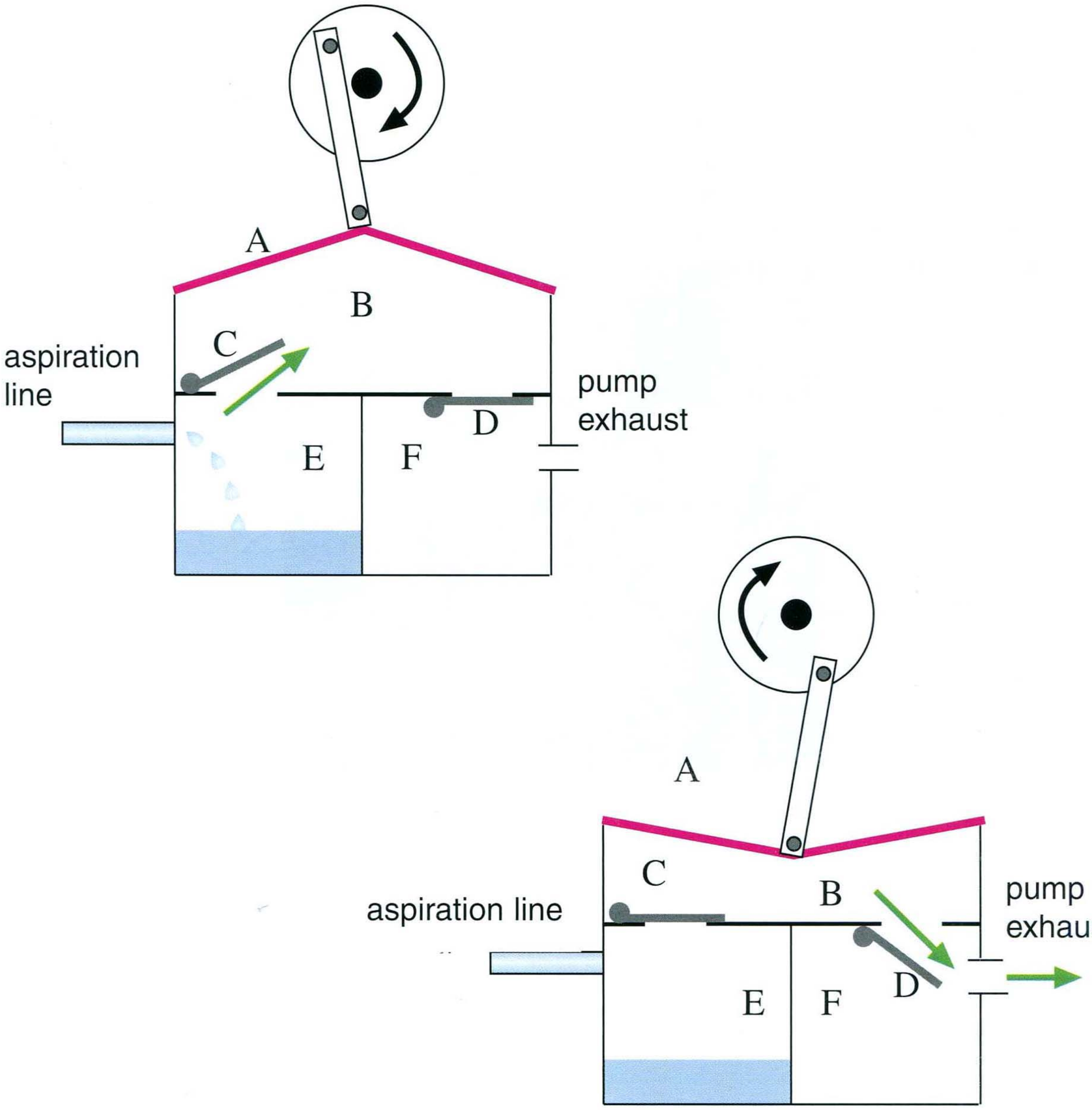

A
B
C
aspiration line
D
pump exhaust
E
F
A
C
B
aspiration line
pump exhaust
D
E
F

FIGURE 1-26

Rotary Vane Pump

A rotary vane pump is illustrated in Figure 1-27. The rotor, which contains freely sliding flat vanes, is mounted eccentrically in the pump housing and is driven by an electric motor. As a vane passes through the expanding volume of inlet area A, vacuum is created that translates to the rigid drainage cassette through the connecting tube as shown. The trapped air is swept through area B, and then is compressed through the decreasing volume of area C so that it is vented out through the pump exhaust. As with the diaphragm pump, the amount of vacuum created is directly proportional to the pump motor speed.

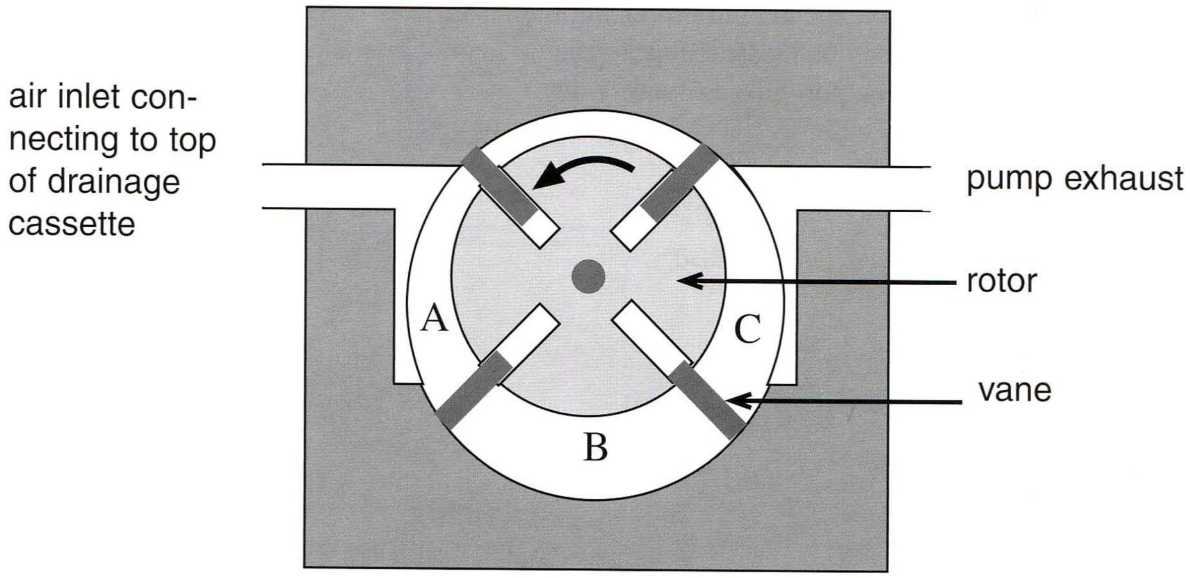

air inlet con-
necting to top
of drainage
cassette
pump exhaust
rotor
vane
A
B
C

FIGURE 1-27

Vacuum Pumps: Direct Control of Vacuum and Indirect Control of Flow

As the surgeon increases the vacuum level in the drainage cassette in Figure 1-28, the flow rate correspondingly increases; note the larger blue arrows in the anterior chamber, as well as the increased number of drips in the drip chamber and drainage cassette in Figure 1-28-2 relative to 1-28-1. Although the vacuum level just inside the phaco tip also increases, it does so to a lesser extent because the relatively large 0.9 mm standard needle aspiration port offers little resistance to the low viscosity irrigating fluid (see Figure 1-41). Therefore, the force of the vacuum in the drainage cassette is mostly expended in producing the faster flow rather than a higher vacuum at the tip; this phenomenon can be measured as a vacuum degradation along the aspiration line with increasing distance from the pump (see Figure 1-42).

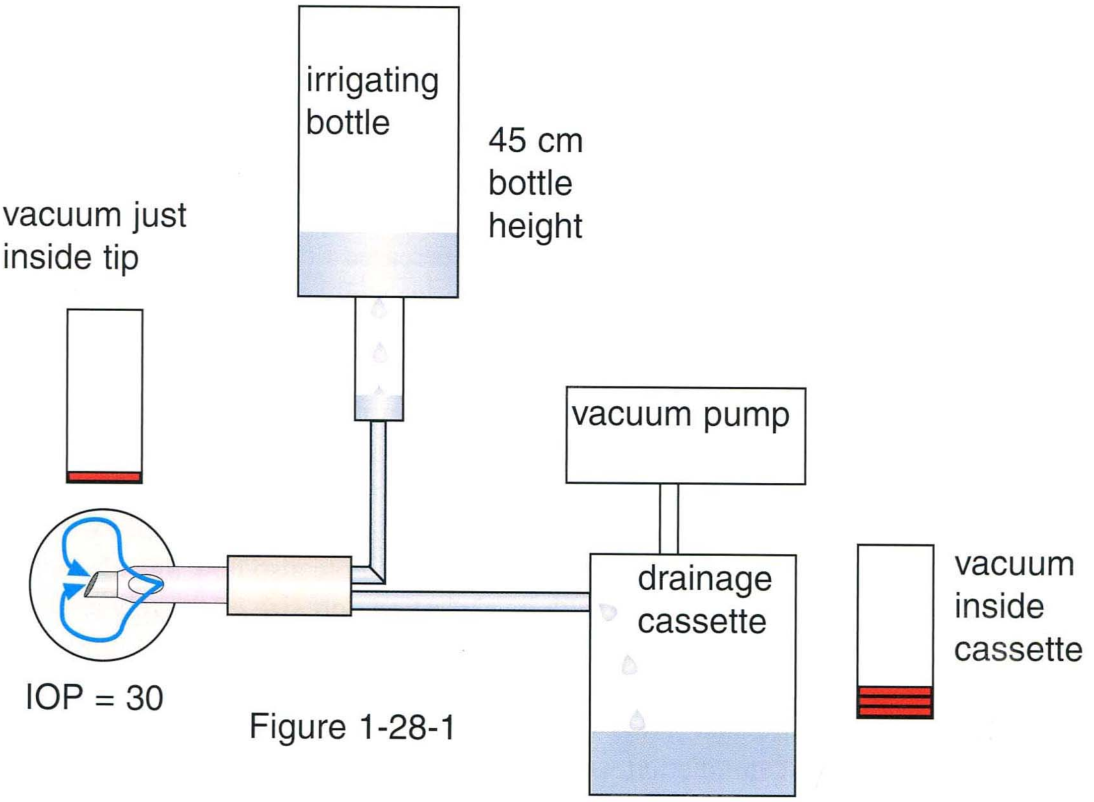


Figure 1-28-1

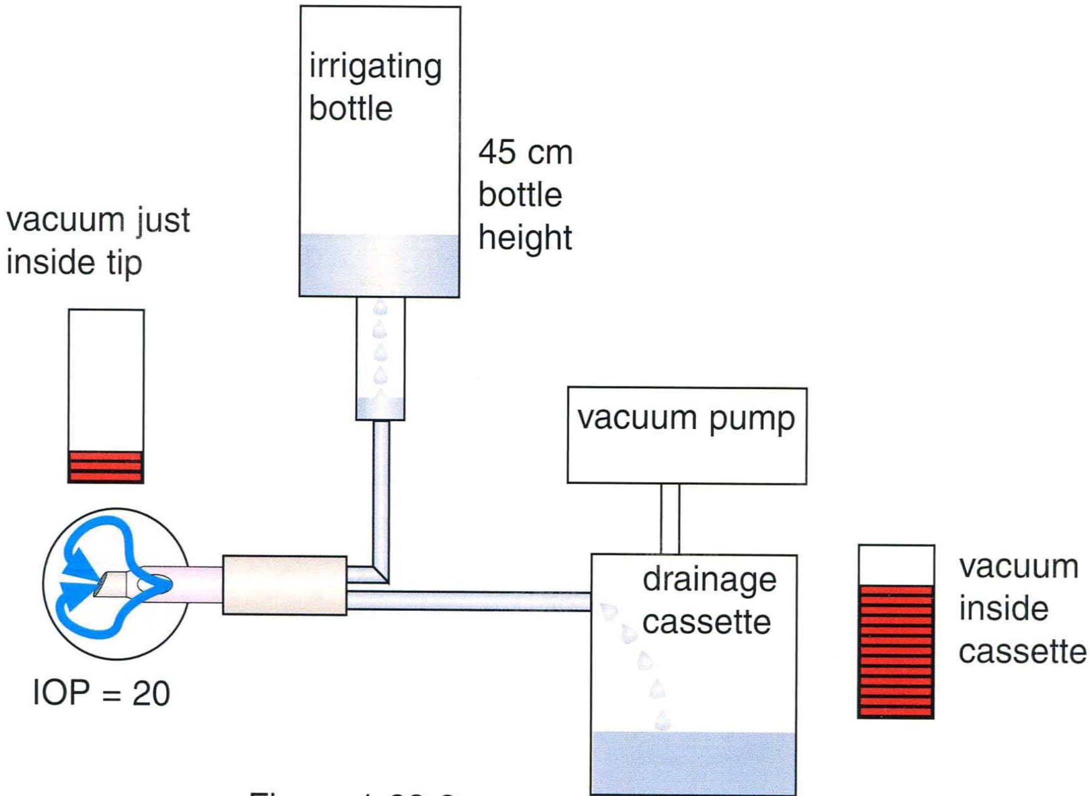


Figure 1-28-2

FIGURE 1-28

Vacuum and Flow Pumps: Flow Resistance

If a higher resistance 0.3 mm diameter aspiration port (ie, an IA tip) was substituted for the phaco tip (0.9 mm diameter aspiration port) in Figure 1-29-1 (note: identical to Figure 1-28-2), the vacuum inside the tip would be higher (but still not as high as in the cassette) and the flow would be lower (Figures 1-29-2 and 1-40A). This principle of decreased flow caused by decreased effective aspiration port surface area holds true for flow pumps as well as vacuum pumps (albeit not to the same degree; see Figure 1-40B); note in Figure 1-11 how the surface area of the phaco needle's aspiration port is effectively decreased by partial and then complete occlusion of a nuclear fragment, a scenario which would similarly affect a vacuum pump. A pump attempting to pull fluid through a higher resistance, smaller aspiration port will result in higher vacuum at the tip and in the aspiration line relative to a larger aspiration port with lower resistance (see Figure 1-41).

Note how the IOP increases as a result of the decreased flow rate produced by the smaller, higher resistance aspiration port on the IA tip (Figure 1-29-2); note also how this identical fluidic result would be produced by a phaco needle with its aspiration port size effectively reduced to IA port size by a partially occluding nuclear fragment (see Figure 1-29-2 and 1-11). Compare Figures 1-29-2 and 1-28-1; note how the same flow rate (illustrated by the drip chamber and drainage cassette activity) and bottle height result in the same IOP regardless of the particular aspiration port (resistance) and pump setting combination which produced the flow rate. Note that this IOP is 30 mm Hg rather than a predicted hydrostatic pressure of 33 mm Hg (3 x 11 mm Hg per 15 cm bottle height), with the difference being due to a hydrodynamic state with a modest flow rate as opposed to a hydrostatic state without any flow (see discussion of Bernoulli's equation with Figure 1-6). Recall also Figure 1-10A, which illustrates how IOP decreases as increased pump function causes an increased flow rate. Both Figures 1-10A and 1-29 assume a constant bottle height, which leads to increased IOP with decreased flow rate. **Therefore, in order to maintain a given IOP as the flow rate is varied, the bottle height must be adjusted accordingly (eg, lowering the bottle height when decreasing the flow rate).**

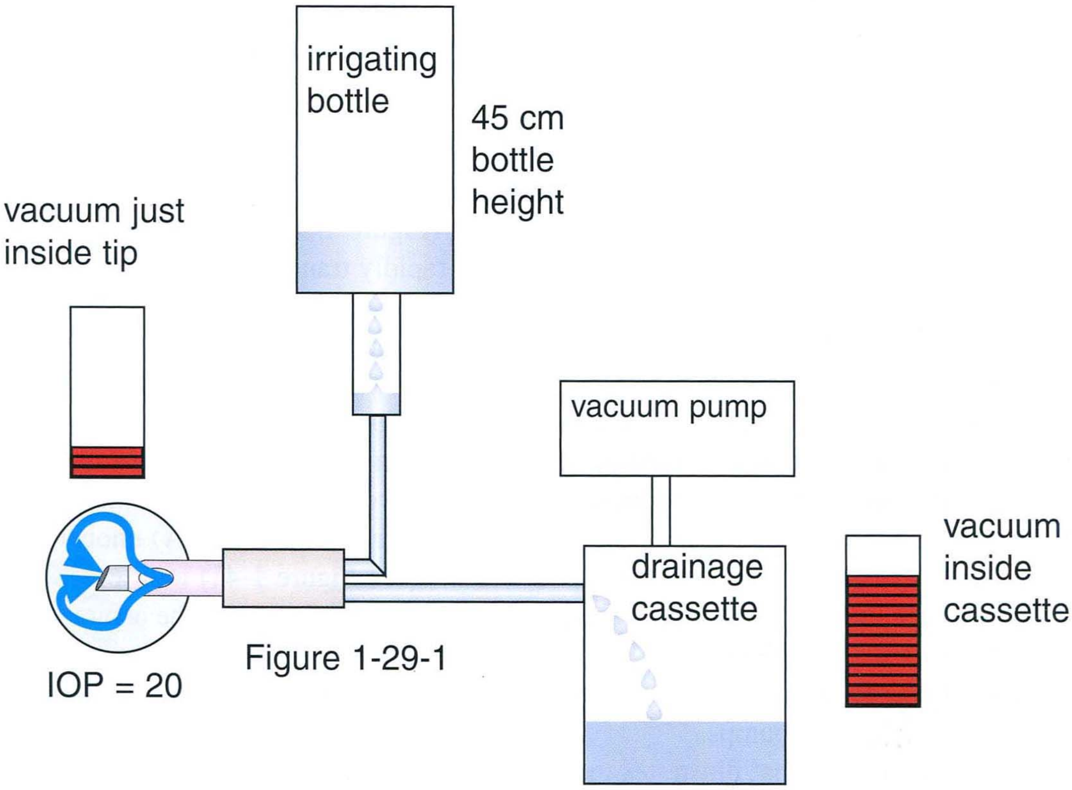


Figure 1-29-1

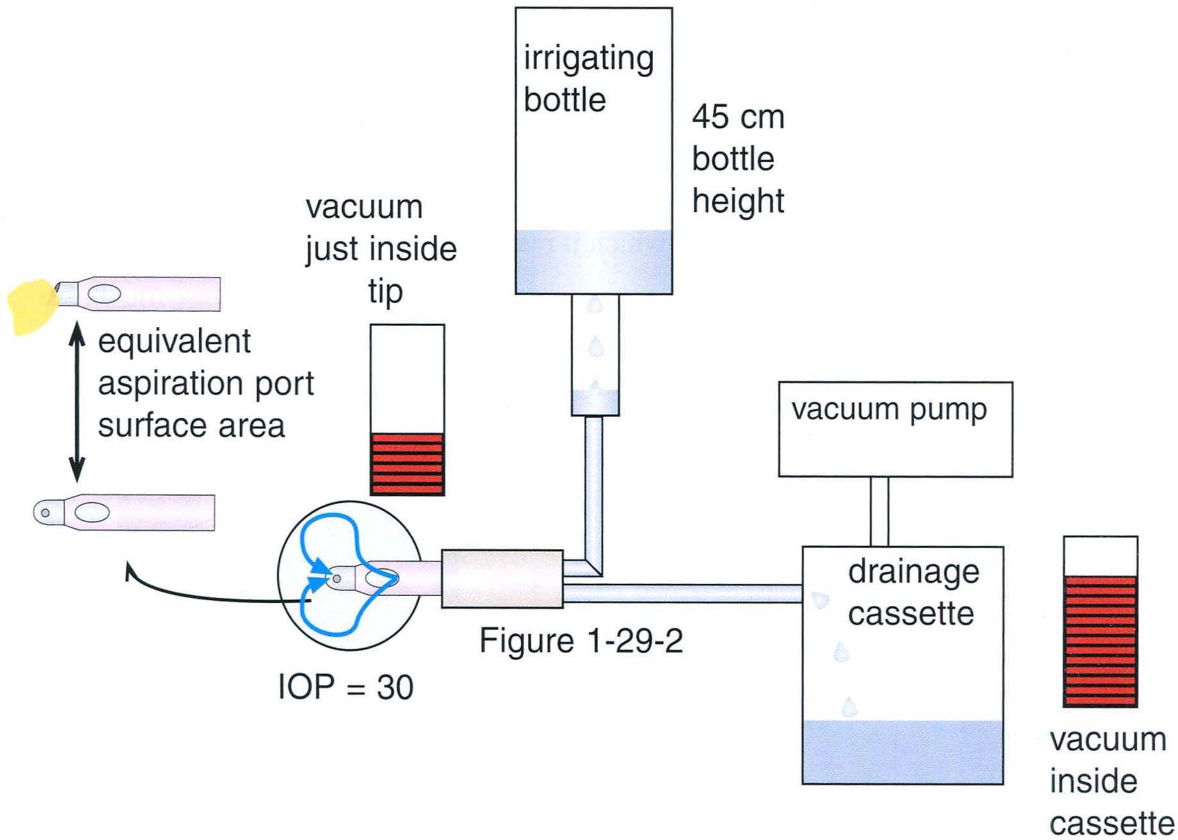


Figure 1-29-2

FIGURE 1-29

Vacuum Pumps: Control of Flow and Grip; Vacuum Transfer Upon Tip Occlusion

By allowing indirect control of flow when the phaco tip is unoccluded (see Figure 1-28), the vacuum pump allows the surgeon to titrate intraocular currents in order to attract material (ie, a chopped nuclear fragment) to the tip's aspiration port (Figure 1-30-1). Once the port is occluded by such a fragment, flow is interrupted; vacuum then rapidly transfers from the drainage cassette along the aspiration line to the occluded aspiration port, where it grips the occluding fragment in direct proportion to the level of vacuum (Figure 1-30-2). Note that the vacuum is now equal inside of the phaco needle and inside the drainage cassette, as well as at every point in between the two. **Both flow and vacuum pumps require complete occlusion of the aspiration port in order to build vacuum at the port to the maximum preset level and to effectively transmit this gripping force to the occluding lens fragment**. The one relative exception to this rule is when a flow pump is driven at a sufficient pump speed through a high resistance (eg, IA) unoccluded aspiration port such that vacuum builds in the aspiration line (see Figure 1-41) to a level which might reach a given vacuum limit preset. However, this vacuum is just inside of the aspiration port, and a fragment must still completely cover and occlude the port in order for the vacuum to grip it and hold it firmly to the tip with a force that is proportionate to the amount of vacuum; this is also true for both flow and vacuum pumps.

An easy experiment that illustrates the above principles utilizes a common household canister-type vacuum cleaner, which typically houses a rotary vane vacuum pump. If the round plastic nozzle at the end of the hose (without any brush or other attachments) is placed against the corner of a small (eg, 2 x 4 x 4 inch) wooden block, the nozzle will be unable to pull the block because the vacuum is driving flow of air around the block into the incompletely occluded nozzle opening (aspiration port). However, if the nozzle is simply placed perpendicular against one of the block's flat surfaces so that the nozzle is completely occluded, sufficient grip will ensue which will allow the block to be pulled along the surface on which it rests.

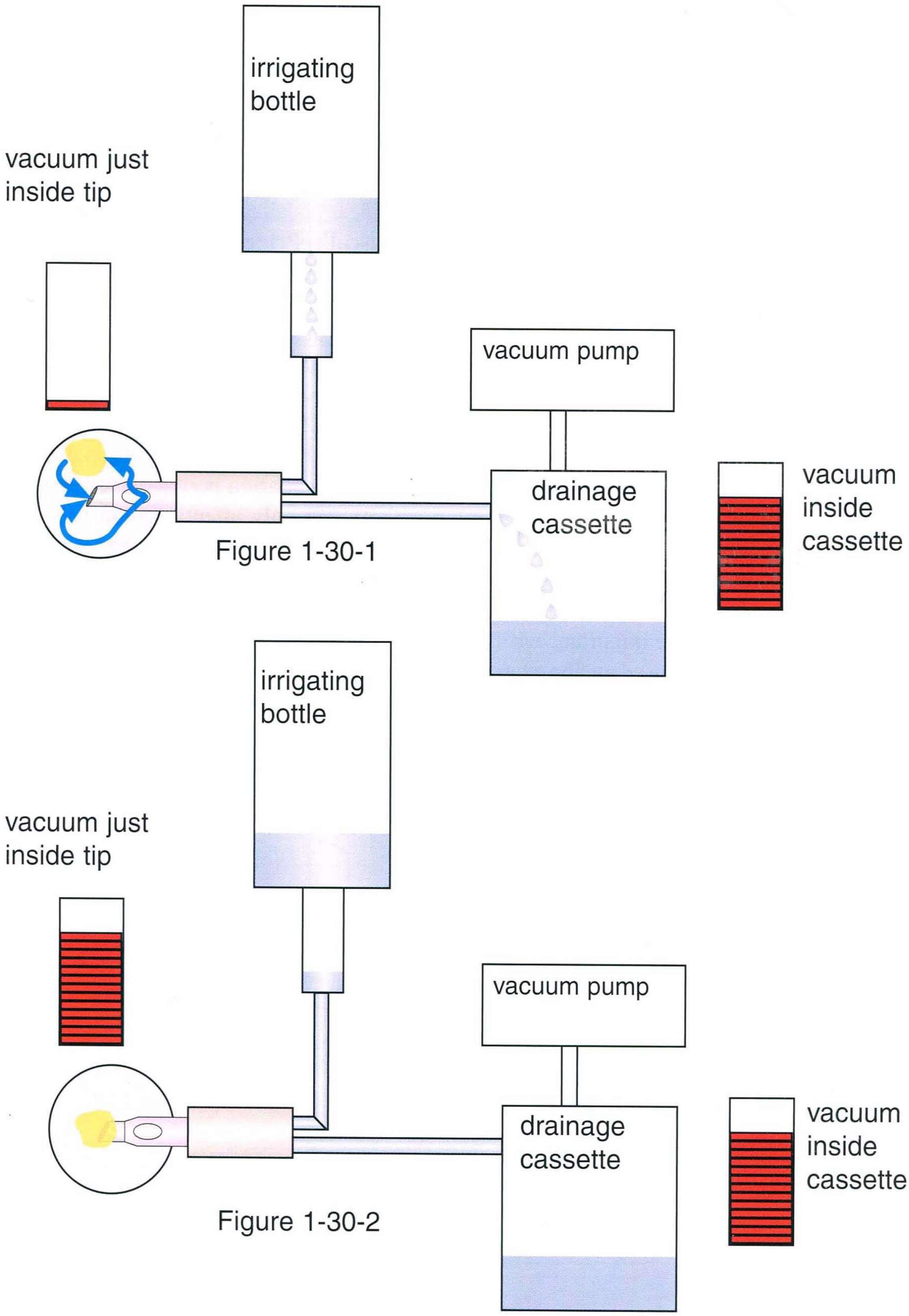

irrigating bottle
vacuum just inside tip
vacuum pump
drainage cassette
vacuum inside cassette
Figure 1-30-1
irrigating bottle
vacuum just inside tip
vacuum pump
drainage cassette
vacuum inside cassette
Figure 1-30-2

FIGURE 1-30

Vacuum Pumps: Direct Control of Vacuum and Grip

With tip occlusion and vacuum transfer from the cassette to the tip (see Figure 1-30), the level of vacuum is the same along this portion of the machine's fluidic circuit between these two points. Note the identical vacuum meter readings both at the cassette and just inside the tip. At this point, the surgeon can titrate the amount of grip from higher (Figure 1-31-1) to lower (Figure 1-31-2) appropriately by titrating the pump vacuum with linear pedal control; the vacuum at the tip will promptly respond proportionately according to **Pascal's Principle**, which states that any change in pressure applied to an enclosed fluid will be transmitted undiminished to all parts of that fluid as well as its enclosing surface, including in this case the nuclear fragment. By titrating the commanded vacuum appropriately to the nuclear density that is occluding the tip, the surgeon has at his or her disposal two distinct clinical functions available, that of gripping in pedal position 2 and that of aspiration in position 3 (recall Figure 1-4).

Note the similarity between Figure 1-31 and Figure 1-12, in which linear pedal control is used to control applied vacuum (and therefore applied grip) within position 2 of phaco mode, seen as a side view of a Dual Linear Pedal (Figure 1-5). Once the aspiration port is occluded and flow ceases, control inputs via the foot pedal to pump activity can only affect vacuum between the occlusion and the pump, regardless of pump type. Therefore, linear control of the vacuum limit (flow pump) and linear control of commanded vacuum (vacuum pump) produce the same clinical result of titratable grip and deformational force of the nuclear fragment that is occluding the phaco needle's aspiration port. The importance of linear control of grip is illustrated in Figure 3-31C, in which excessive vacuum caused an abrupt aspiration of part of an occluding fragment, resulting in loss of the vacuum seal and subsequent loss of control and grip. The surgeon in this case would re-engage the fragment with the aspiration port but raise the foot pedal somewhat to produce a lower and more appropriate vacuum for this given nuclear density.

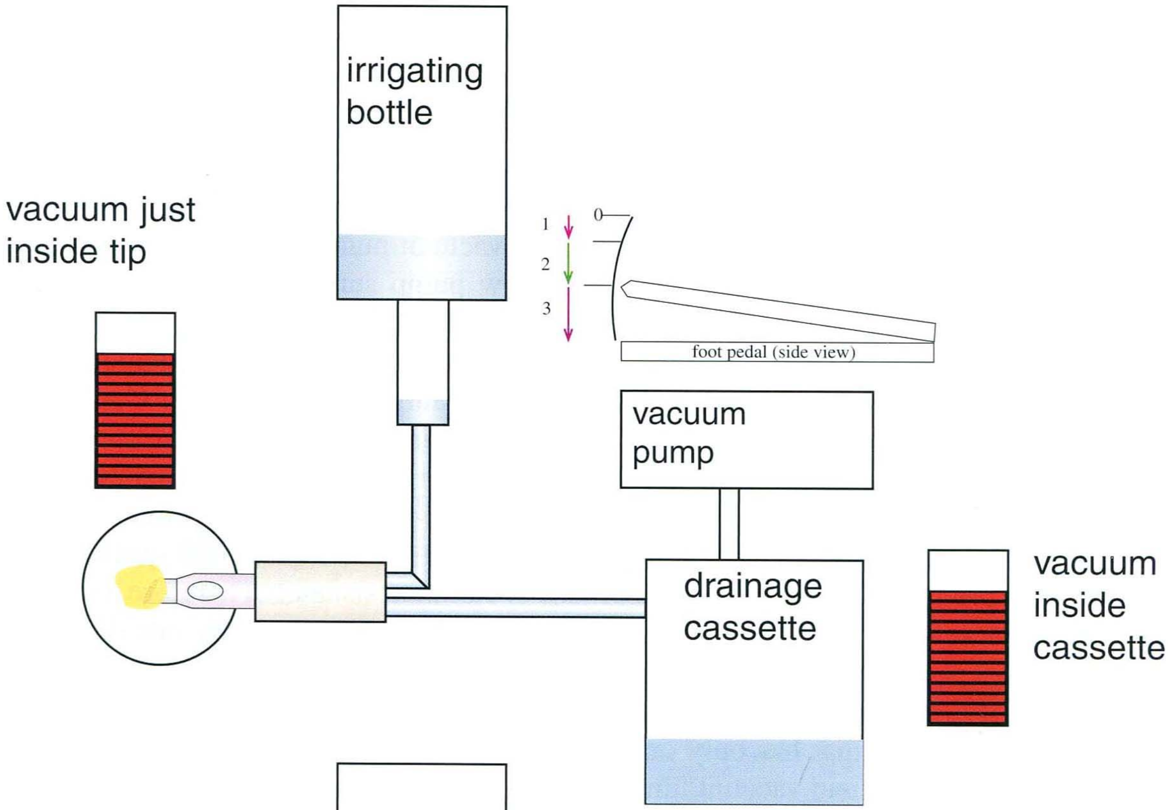


Figure 1-31-1

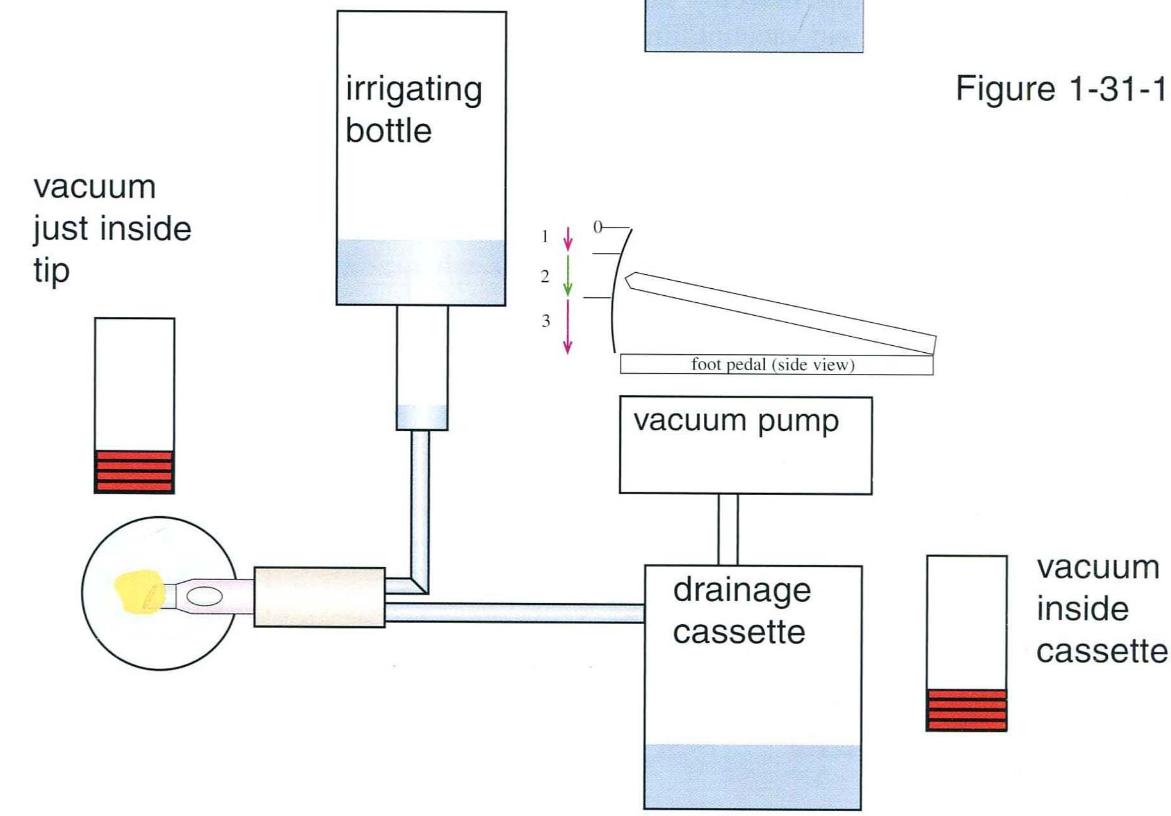


Figure 1-31-2

FIGURE 1-31

Vacuum Pump Emulation by Flow Pumps

In contrast to their similarity in controlling grip with an occluded aspiration port (see preceding page), vacuum pumps and flow pumps differ considerably with regard to control inputs when the aspiration port is not occluded. In order to increase the strength and speed of the anterior chamber currents that draw material to the tip, the vacuum pump surgeon increases the commanded vacuum level (Figure 1-28), whereas the flow pump surgeon must increase the commanded flow rate (not the vacuum limit) to achieve the same clinical result (see Figure 1-10). However, some relative exceptions exist to this rule in the form of a few flow pump machines.

For example, the machines from Bausch & Lomb Surgical (Millennium Concentrix and Peristaltic) and Geuder (peristaltic) offer the option of running the machine in a vacuum emulation mode; instead of commanding flow in position 2, the surgeon commands vacuum just as in a venturi pump. If the pressure transducer (see Figure 1-16) measures a vacuum lower than the commanded level, then a feedback algorithm drives the pump at a faster rotational speed; the subsequent faster flow produces a higher vacuum because of fluidic resistance. Therefore, commanding a higher vacuum level drives the pump head faster and produces a higher flow rate (Figure 1-32); compare this concept to Figure 1-28. The advantage of this control strategy is combining a peristaltic's freedom from a compressed gas tank with the ability to use the relative simplicity of a vacuum pump control system that has only one fluidic parameter (commanded vacuum) instead of two (commanded flow rate and vacuum limit).

The Alcon Infiniti has a clinically similar control strategy whereby the surgeon has the option of linear control of flow in position 2 when the tip is not occluded, and linear control of vacuum limit (therefore grip) when the tip is occluded. The end result is essentially identical to a venturi or other vacuum pump in that the surgeon simply depresses the pedal farther in position 2 to more strongly draw material to the unoccluded tip, and to more strongly grip material that is occluding the tip. Always bear in mind these clinical correlates when adjusting Phacodynamic machine parameters.

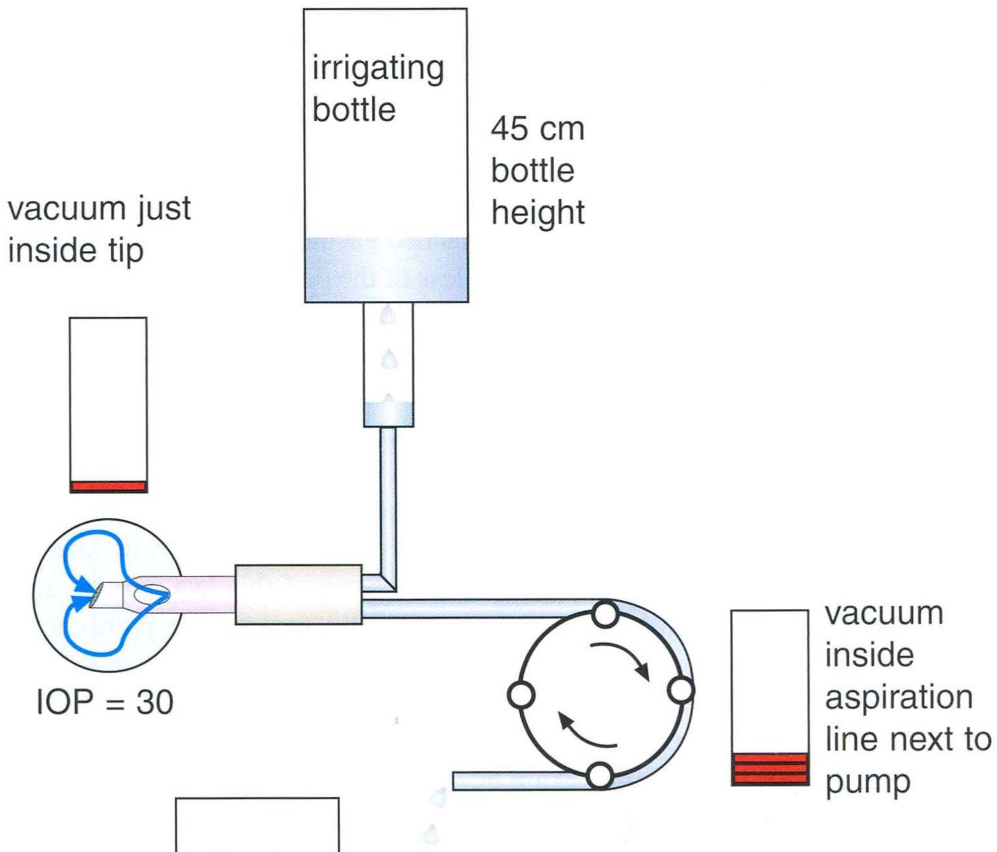


Figure 1-32-1

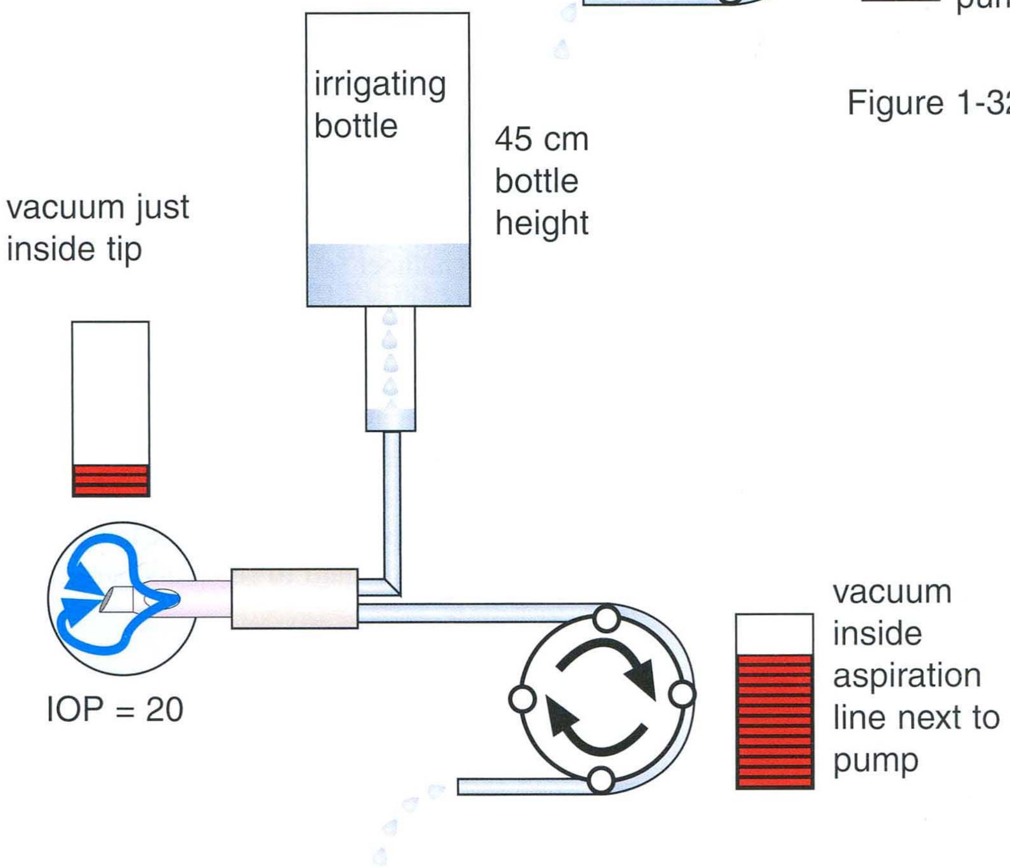


Figure 1-32-2

FIGURE 1-32

Vacuum Pump Emulation by Flow Pumps (continued)

In a flow pump's venturi emulation mode, as discussed with Figure 1-32, the pump motor speed can vary as needed to maintain a commanded vacuum (as determined by the foot pedal position and the maximum vacuum preset) regardless of the degree of tip occlusion in exactly the same manner as a vacuum pump. Indeed, the fluid in the aspiration line is oblivious to the type of pump that is creating a given vacuum (which is in turn inducing flow in proportion to the amount of that vacuum). Note the equivalent performance of the venturi vacuum pump vs the Concentrix flow pump in vacuum mode in Figure 1-33; **a given commanded vacuum level produces a given flow rate regardless of the pump type that produced the vacuum**.

Whereas flow pumps may be operated in a vacuum emulation mode as discussed above, no current vacuum pumps offer a true flow emulation mode whereby a flow rate can be dialed into a machine panel preset. However, the clinical significance of this fact may be questionable for two reasons. First, the flow control on flow pumps actually controls the pump head rotational speed while actual flow typically varies according to effective aspiration port size (fluidic resistance), as shown in Figures 1-11 and 1-34. Second, flow can be indirectly but adequately controlled with an unoccluded aspiration port and linear vacuum control on vacuum pump machines; control inputs (ie, foot pedal position within range 2) are qualitatively based on visual feedback through the operative microscope and do not require an arbitrarily special flow control on the machine's panel. In fact, the only theoretical advantage of a true flow pump might be with regard to chamber depth and stability at high vacuum settings and an unoccluded aspiration port.

For example, a flow pump surgeon who requires high vacuum (eg, for chopping techniques) may still have a gentle low flow environment by setting a low to moderate commanded flow along with a high vacuum limit, whereas a vacuum pump surgeon in this setting might conceivably need to contend with a more shallow and unstable anterior chamber (at the same bottle height as the flow pump example) caused by the faster flow rate induced by the high commanded vacuum setting (Figure 1-28). However, this advantage is less distinct when compared to a vacuum pump controlled by a Dual Linear pedal, which allows the surgeon to limit high vacuum only to those surgical instances that require a firm grip and during which the aspiration port is fully occluded (ie, no flow). Other methods of flow attenuation with vacuum pumps at high vacuum settings include resistive phaco needles (Figure 1-61) as well as aspiration line restrictors such as the STAAR Cruise Control (Figure 1-48-4). Therefore, either a flow pump or vacuum pump can be used effectively as long as they are Phacodynamically optimized with regard to setup and surgeon understanding.

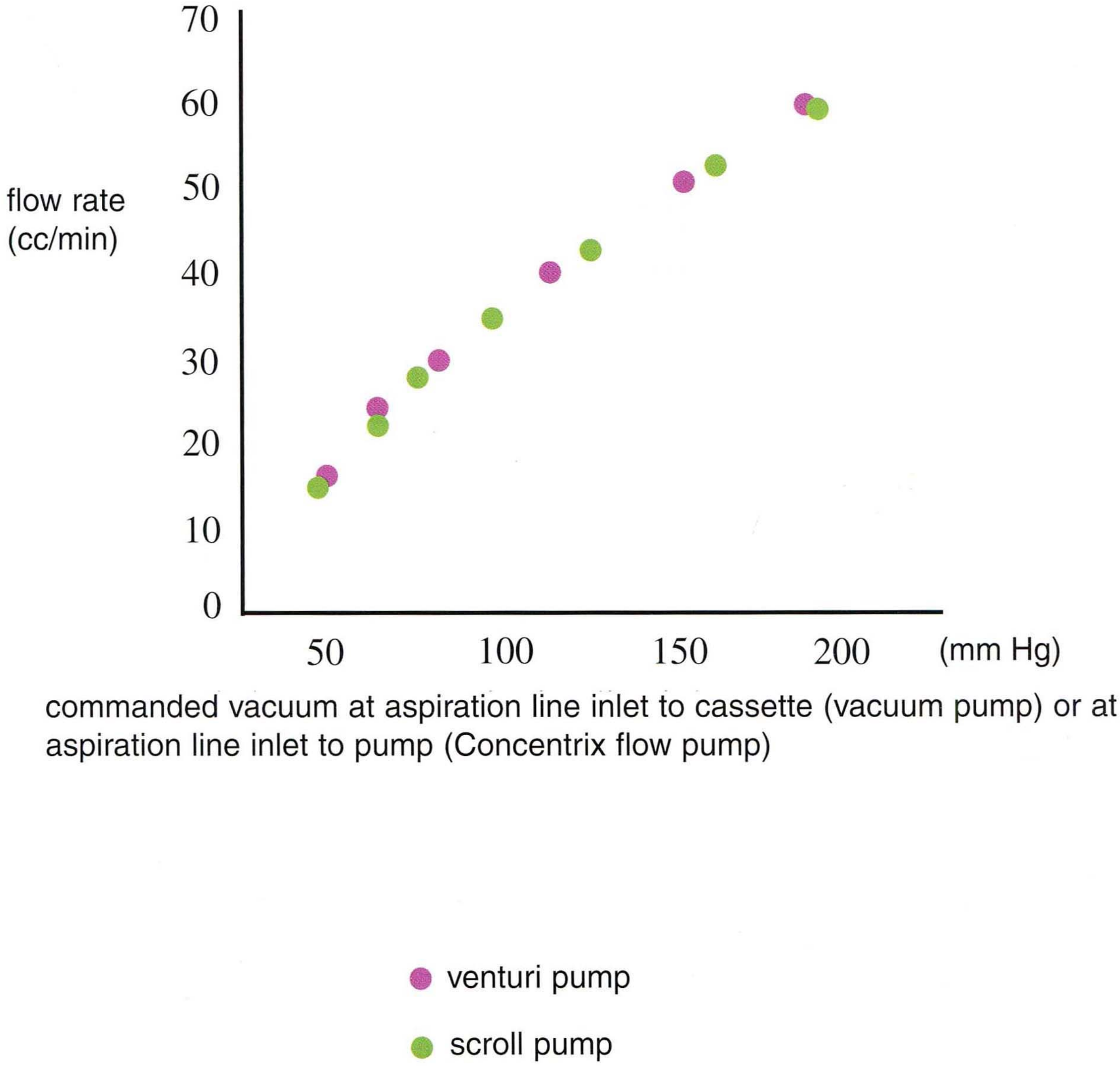

flow rate
(cc/min)
70
60
50
40
30
20
10
0
50
100
150
200
(mm Hg)
commanded vacuum at aspiration line inlet to cassette (vacuum pump) or at aspiration line inlet to pump (Concentrix flow pump)
venturi pump
scroll pump

FIGURE 1-33

Control Strategy: Flow Pump vs Vacuum Pump

When considering a pump that can be used as a flow pump or a vacuum pump (eg, Figures 1-32 and 1-33), it is helpful to review the different ways in which each pump affects a fluidic circuit. For this purpose, viscosity in the aspiration line is a useful differentiator. In Figure 1-34, each pump type is tested using a standard 19 Ga. phaco needle **without occlusion** and with two different fluidic circuit viscosities:

1. Normal saline, which is equivalent to aqueous humor
2. A higher viscosity mixture of saline plus viscoelastic

Note the upper diagram in Figure 1-34, which represents a flow priority mode of pump operation that is available on any flow pump. Flow decreases only slightly when comparing low viscosity to high viscosity solutions as expected from the discussion of fluidic resistance with Figure 1-40B. However, note the much more significant change in vacuum, with a higher vacuum level in the saline plus viscoelastic section caused by the pump pulling harder against the higher viscosity fluid in order to maintain a commanded flow rate of 17 cc/min (which decreases just slightly to 16 cc/min as the pump pulls against the higher resistance). Similarly, note the lower diagram representing a vacuum priority feedback control that would be present on any vacuum pump as well as certain flow pumps in venturi emulation (eg, Bausch & Lomb Concentrix and Advanced Flow System); the commanded vacuum level of 100 mm Hg is the same in the two different viscosities. However, the saline-only circuit has a significantly higher flow rate (21 vs 7) because it offers less resistance to flow for this given vacuum level. In even more basic terms, with the flow pump the commanded flow remains essentially constant (purple bars), while the aspiration line vacuum varies with fluidic resistance (green bars). Conversely, the commanded vacuum level on a vacuum pump remains constant (green bars), while the flow varies with fluidic resistance (purple bars).

This experimental setup has several clinical corollaries. For example, fluidic circuit viscosity increases during phacoemulsification as the nuclear emulsate accumulates in the aspiration line in proportion to the density of the nucleus and the speed of phacoaspiration. Of course, viscoelastic also increases the fluidic circuit's viscosity. The effect of these different viscosities is usually evident even after the causative material is aspirated from the anterior chamber because it still must traverse the length of the aspiration line before its effect is eliminated from the fluidic circuit. Therefore, bear in mind the effects of Figure 1-34 when using a vacuum pump (or a flow pump in a vacuum priority mode). A decreasing effective flow rate (caused by increased viscosity in the aspiration line) will produce decreased followability as well as less effective ultrasonic tip cooling; the surgeon should appropriately compensate by increasing vacuum level accordingly, preferably with linear control based on visual feedback through the operating microscope with regard to speed and strength of anterior chamber currents.

For additional information on control strategy for flow pumps vs vacuum pumps, see Figure 2-7A.

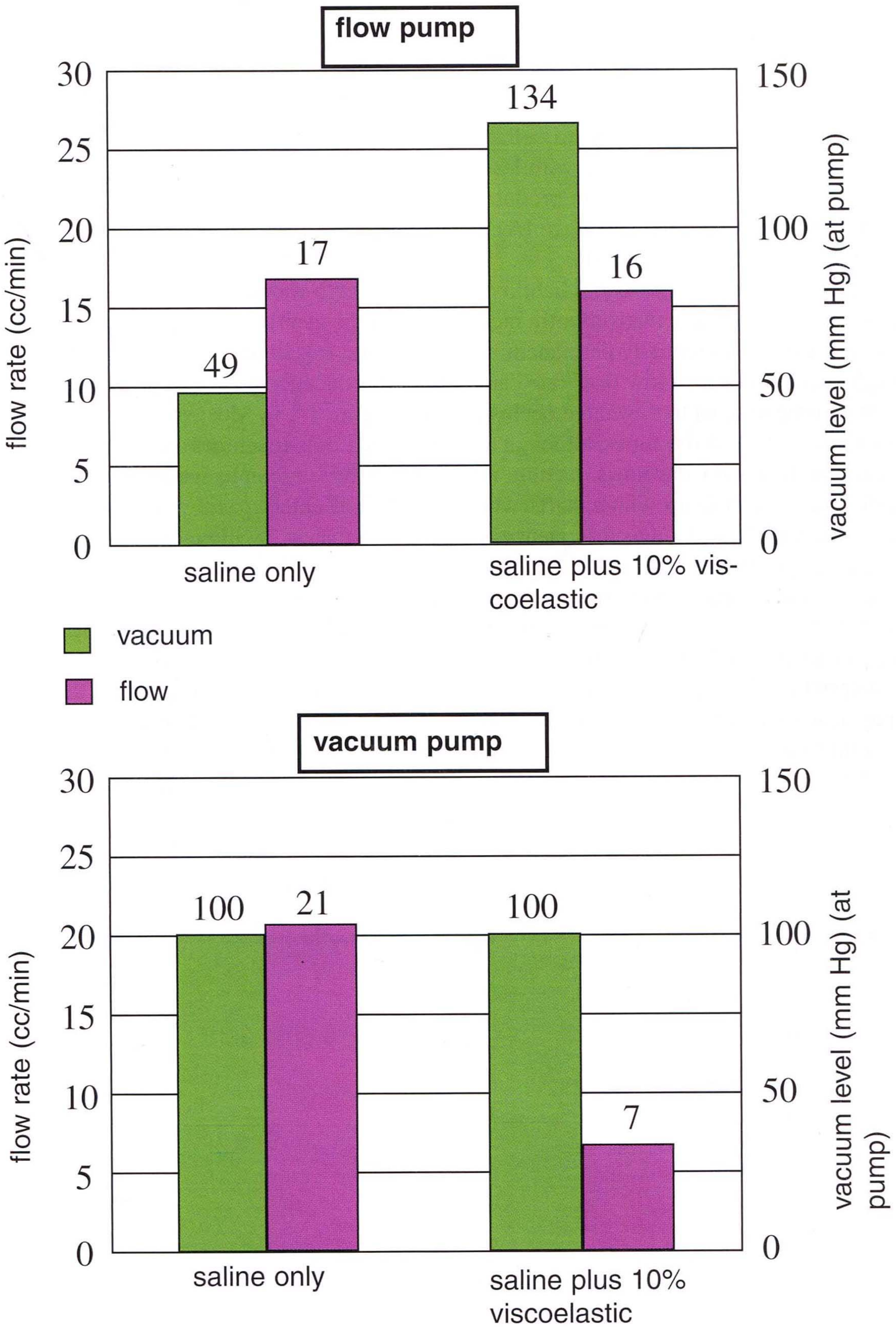

flow pump
30
25
20
15
10
5
0
flow rate (cc/min)
150
100
50
0
vacuum level (mm Hg) (at pump)
49
17
134
16
saline only
saline plus 10% vis-coelastic
vacuum
flow
vacuum pump
30
25
20
15
10
5
0
flow rate (cc/min)
150
100
50
0
vacuum level (mm Hg) (at pump)
100
21
100
7
saline only
saline plus 10% viscoelastic

FIGURE 1-34

Rise Time: Vacuum Pumps

Because no rollers are required to collapse the tubing (as with peristaltic pumps), vacuum pumps can employ more rigid tubing with less compliance. This lower compliance coupled with these pumps' inherently rapid vacuum production, as well as the short times needed for vacuum transfer from the cassette to the phaco (or IA) tip (Figure 1-30), result in low rise times with most vacuum pumps.

Low rise times can be a potential liability when using high vacuum techniques such as chopping. If unwanted material is inadvertently incarcerated in the aspiration port, the surgeon has little time to react before potentially permanent damage occurs. Recall that when using a flow pump with a high vacuum preset, a low flow rate can be set to produce longer rise times which give the surgeon more time to react to unwanted occlusions (see Figure 1-13). Most vacuum pumps do not allow attenuation of rapid rise times, although the Bausch & Lomb machines are exceptions. These pumps (both venturi and Concentrix vacuum mode) allow the surgeon to set a time delay for full commanded vacuum buildup which starts when the surgeon enters pedal position 2. However, once this delay has elapsed, any subsequent engagement of material will be exposed to a typically rapid vacuum pump rise time.

An even better solution to this issue is the previously discussed Dual Linear foot control on the Bausch & Lomb Millennium (see Figure 1-5). With linear control of vacuum in phaco mode, the surgeon can approach material with safer lower vacuum levels and increase it only after the desired material is positively engaged. Furthermore, the rise time in this case will be determined by the physical speed of pedal movement through its linear vacuum travel; attenuation of rapid vacuum pump rise times is accomplished simply by more slowly depressing the pedal (Figures 1-35 and 1-39).

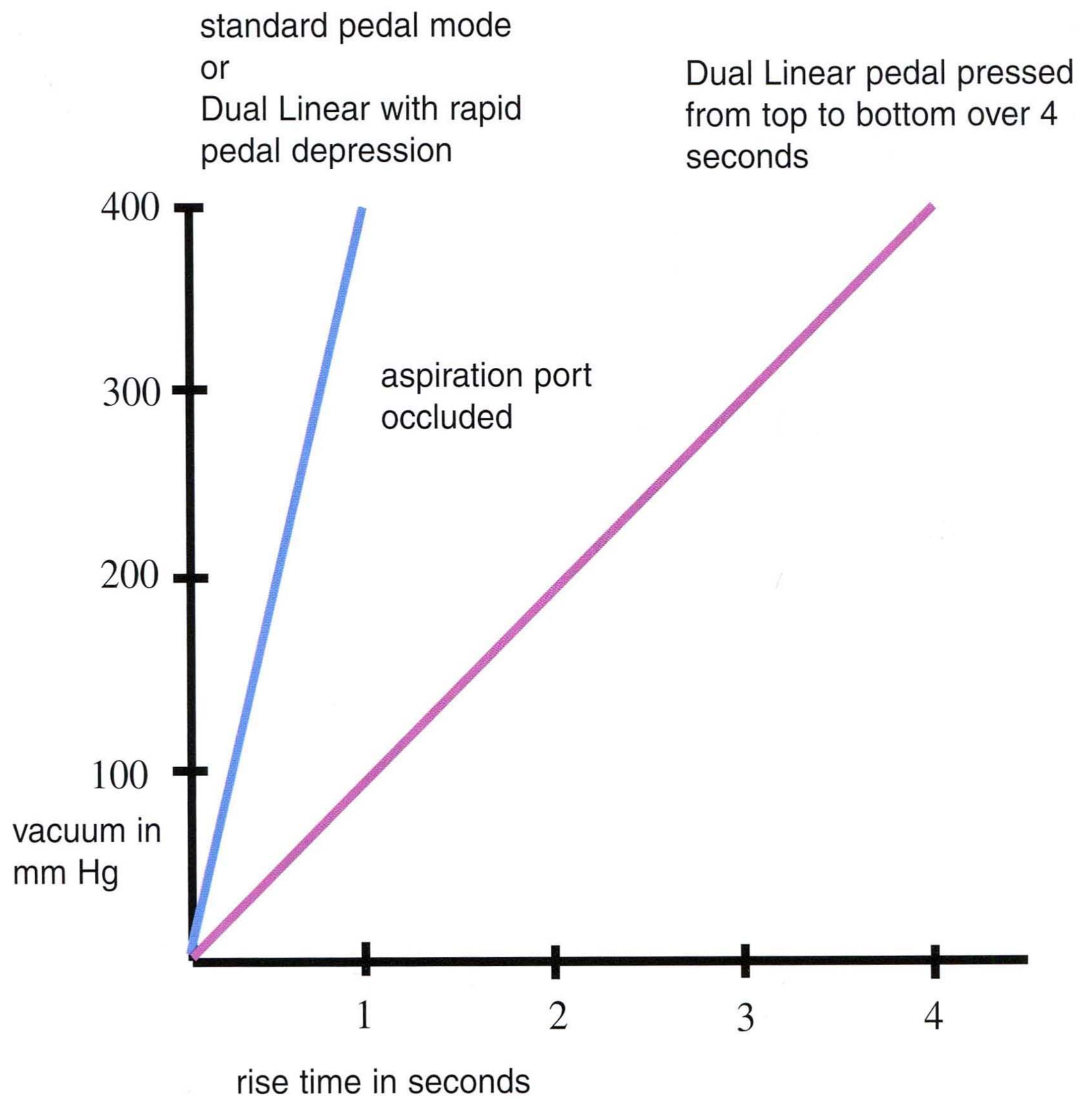

standard pedal mode
or
Dual Linear with rapid
pedal depression
Dual Linear pedal pressed
from top to bottom over 4
seconds
400
300
200
100
aspiration port
occluded
vacuum in
mm Hg
1
2
3
4
rise time in seconds

FIGURE 1-35

Vacuum Pumps: Relationship Between Rise Time and Vacuum

Note how Figure 1-36 differs from the flow pump schematics (eg, Figure 1-16) with regard to the lack of a flow rate parameter adjustment; this is arguably a clinically arbitrary omission in that flow can be indirectly controlled by applied vacuum if the aspiration port is not completely occluded (see Figure 1-28). Furthermore, whereas rise time (with an occluded tip) can be varied with a flow pump by changing the flow rate parameter adjustment (pump speed), rise time can be controlled without flow rate adjustment on a vacuum pump if the surgeon utilizes Dual Linear Pedal control (see Figures 1-35 and 1-39). Recall that the actual vacuum on these schematics is measured by the machine's pressure transducer which is typically connected to the drainage cassette; it is therefore not an accurate reflection of vacuum just inside the aspiration port unless the port is completely occluded (see Figure 1-30).

At time zero in Figure 1-36, the tip is occluded and the linear control pedal is abruptly pushed from position 0 to a halfway point in position 2; this pedal position coupled with a maximum vacuum preset of 400 mm Hg will yield a **Maximum Potential Vacuum (MPV)** of 200 mm Hg, but at time 0.25 sec, vacuum has only risen to 100 mm Hg (assuming a rise time of 200 mm Hg/0.5 sec as shown in Figure 1-38). Just as with the preceding flow pump rise time examples, flow has stopped since the aspiration port is completely occluded. There is no dripping in either the drip chamber or the drainage cassette; the arrow in the drainage cassette represents the pulling force exerted on the aspiration line fluid by the vacuum pump.

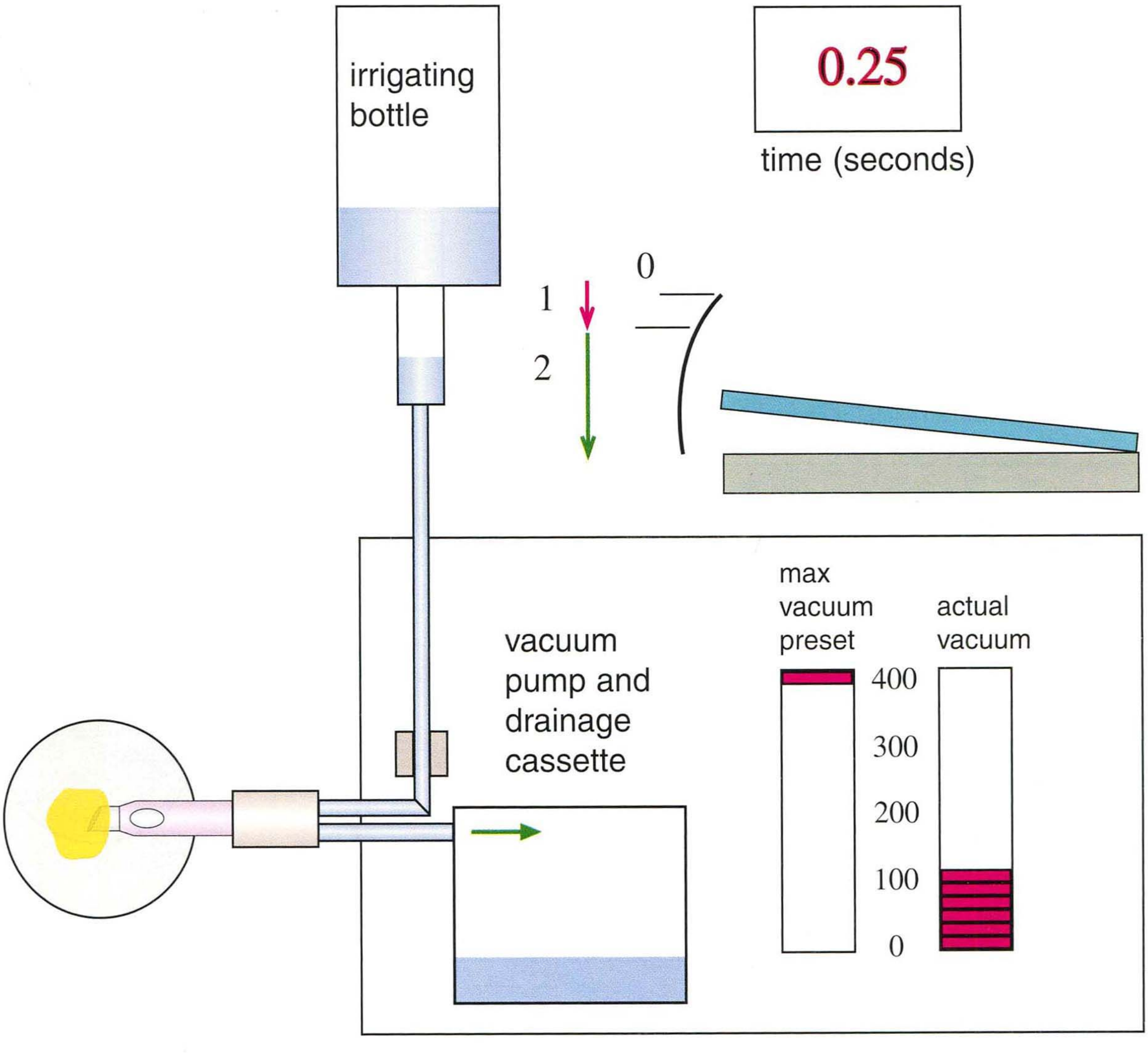

irrigating
bottle
0.25
time (seconds)
0
1
2
vacuum
pump and
drainage
cassette
max
vacuum
preset
actual
vacuum
400
300
200
100
0

Figure 1-36

Vacuum Pumps: Relationship Between Rise Time and Vacuum (continued)

Figure 1-37: At time 0.5 sec after tip occlusion and pedal actuation, actual vacuum has now reached 200 mm Hg, which is the maximum potential vacuum for this combination of pedal position and maximum vacuum preset. Note that the green arrow inside the drainage cassette is now larger, indicating the stronger pull that the higher actual vacuum is exerting on the aspiration line fluid and therefore on the occluding nuclear fragment.

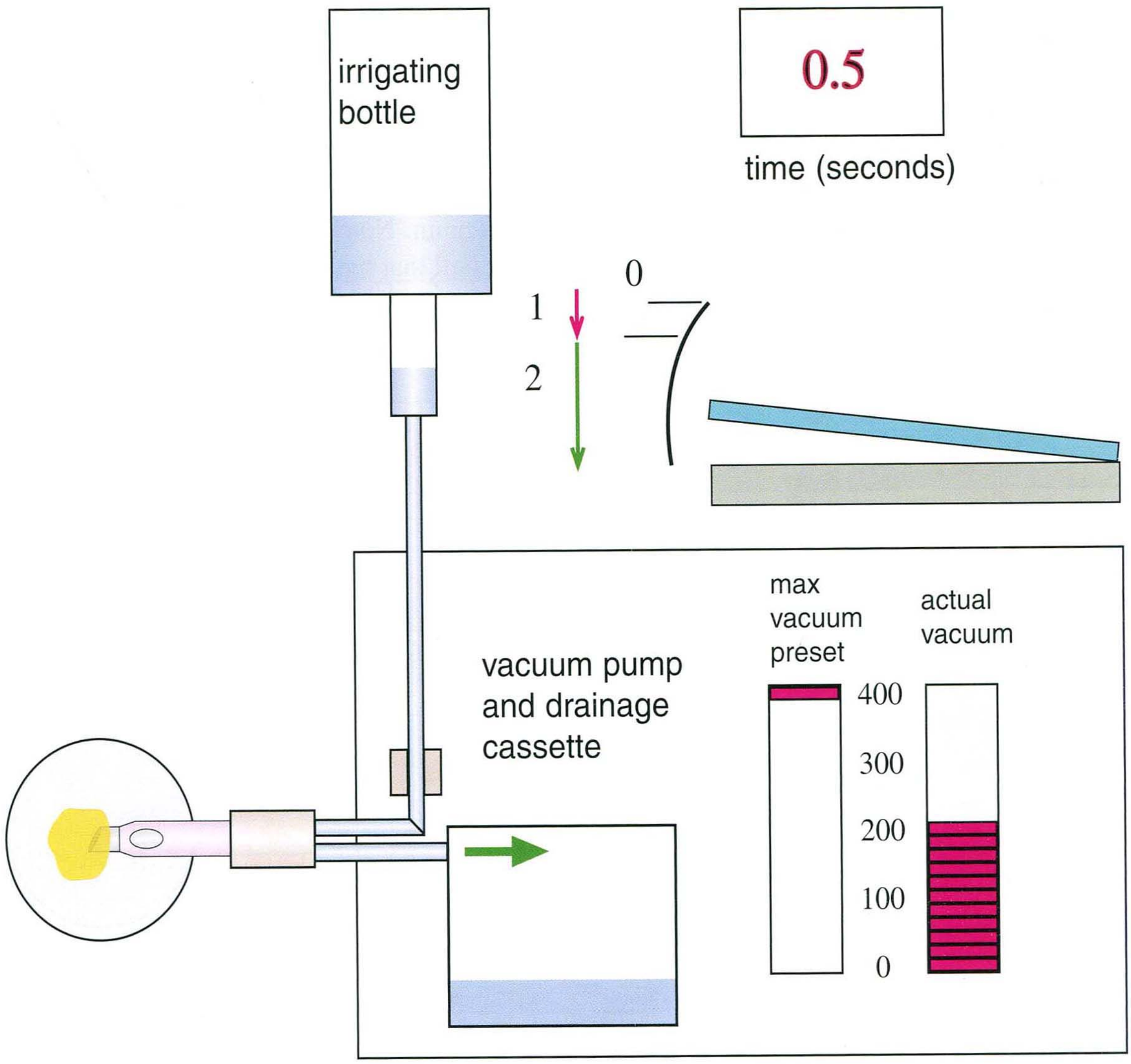

irrigating
bottle
0.5
time (seconds)
0
1
2
max
vacuum
preset
actual
vacuum
vacuum pump
and drainage
cassette
400
300
200
100
0

FIGURE 1-37

Vacuum Pumps: Relationship Between Rise Time and Vacuum (continued)

Figure 1-38: Beginning with time 0.5 sec in Figure 1-37, suppose the pedal was abruptly fully depressed (Figure 1-38) from its original position which was only halfway into position 2. Given the rise time rate of 200 mm Hg/0.5 sec and the starting point of 200 mm Hg, it will take an additional 0.5 sec to reach 400 mm Hg; therefore, the total elapsed time will be 1 sec as illustrated here. Remember to allow for this delay of rise time (see also rise time lag in Figure 1-22) when changing the pedal position to increase linear vacuum. Note also the increased size in the drainage cassette's green arrow, reflecting the stronger pull that the higher actual vacuum level is exerting on the aspiration line fluid and occluding lens fragment as compared to Figure 1-37.

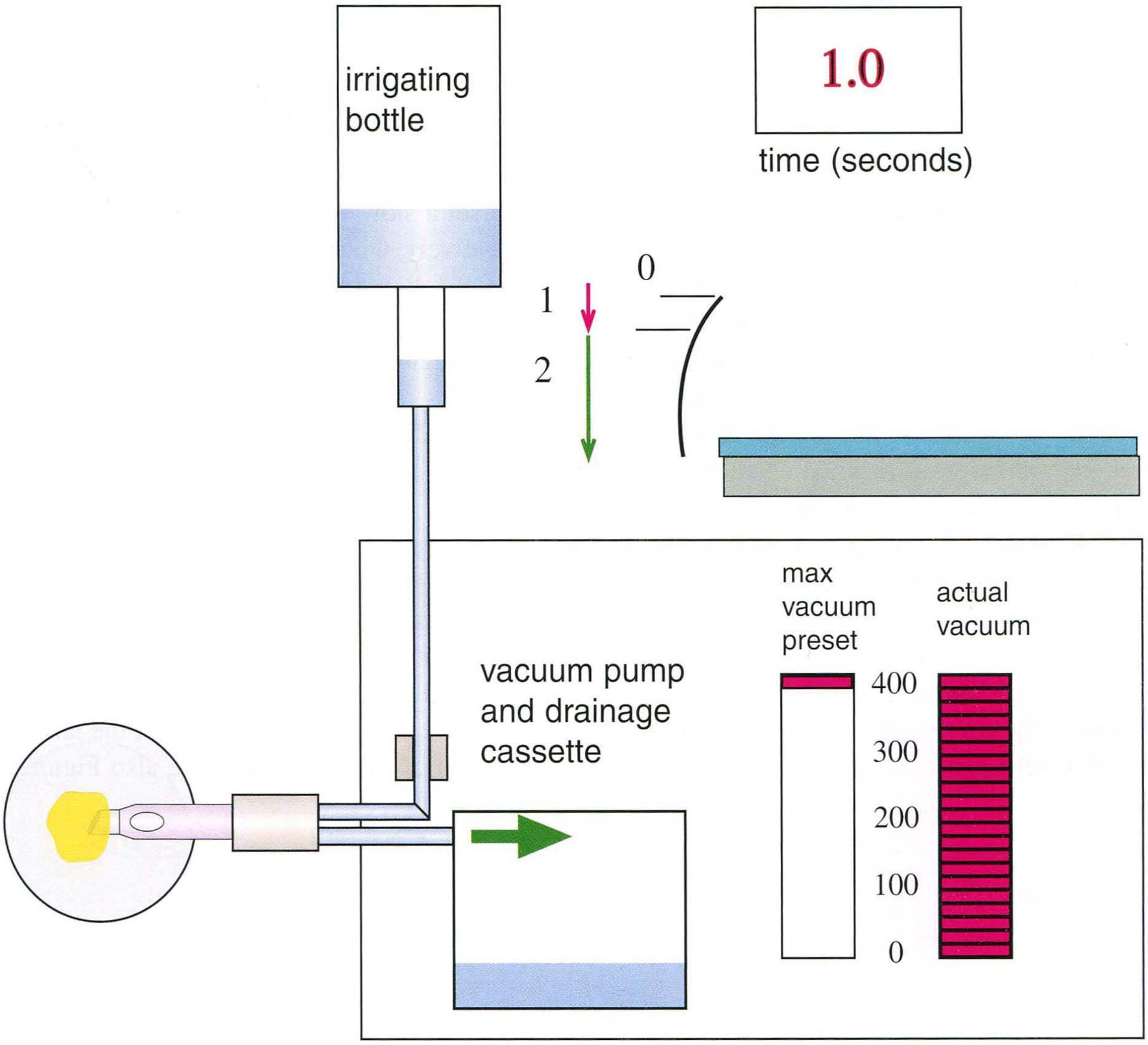

irrigating bottle
1.0
time (seconds)
0
1
2
max vacuum preset
actual vacuum
vacuum pump and drainage cassette
400
300
200
100
0

FIGURE 1-38

Vacuum Pumps: Pedal Control of Rise Time

Figure 1-39: The rise time lag alluded to in Figure 1-38 is usually clinically insignificant with vacuum pumps or with flow pumps operating at a fast flow rate (rotational pump head speed). Indeed, the fast rise times in these cases can be a liability in that the surgeon has little time to react in case of inadvertent incarceration of unwanted material in the aspiration port before dangerously high levels of vacuum build up. By accepting the compromise of a longer rise time with correspondingly slower pedal responsiveness, a surgeon can set a slower flow rate when using a flow pump, thus intentionally inducing a rise time lag. Alternatively, when using a machine with linear control of vacuum in phaco mode (ie, Alcon Infiniti, Bausch & Lomb Surgical Millennium, or AMO Sovereign), the rise time can be lengthened by moving the pedal more slowly through its linear range of travel when the aspiration port is occluded. Figure 1-39 illustrates this concept with the Dual Linear Pedal being depressed through position 2's range over a 4 second time period. Note the times next to the actual vacuum meter indicating that 100 mm Hg was reached at 1 second, 200 mm Hg was reached when the pedal was depressed still further at the 2 second mark, and so on.

Although illustrated here with a vacuum pump, this mechanical control of rise time can be used on both flow pumps (controlling vacuum limit Figure 1-12) as well as vacuum pumps (controlling commanded vacuum Figure 1-31) because the clinical result is identical when the phaco needle's aspiration port is occluded. Pedal control of rise time is particularly effective when using Dual Linear control with its larger range of travel in position 2 (see Figures 1-5 and 1-35). Compare the rise time of 4 sec in Figure 1-39 to the rise time of 1 sec in Figure 1-38, the latter of which would have been produced by abrupt full depression of the foot pedal (see also Figure 1-35).

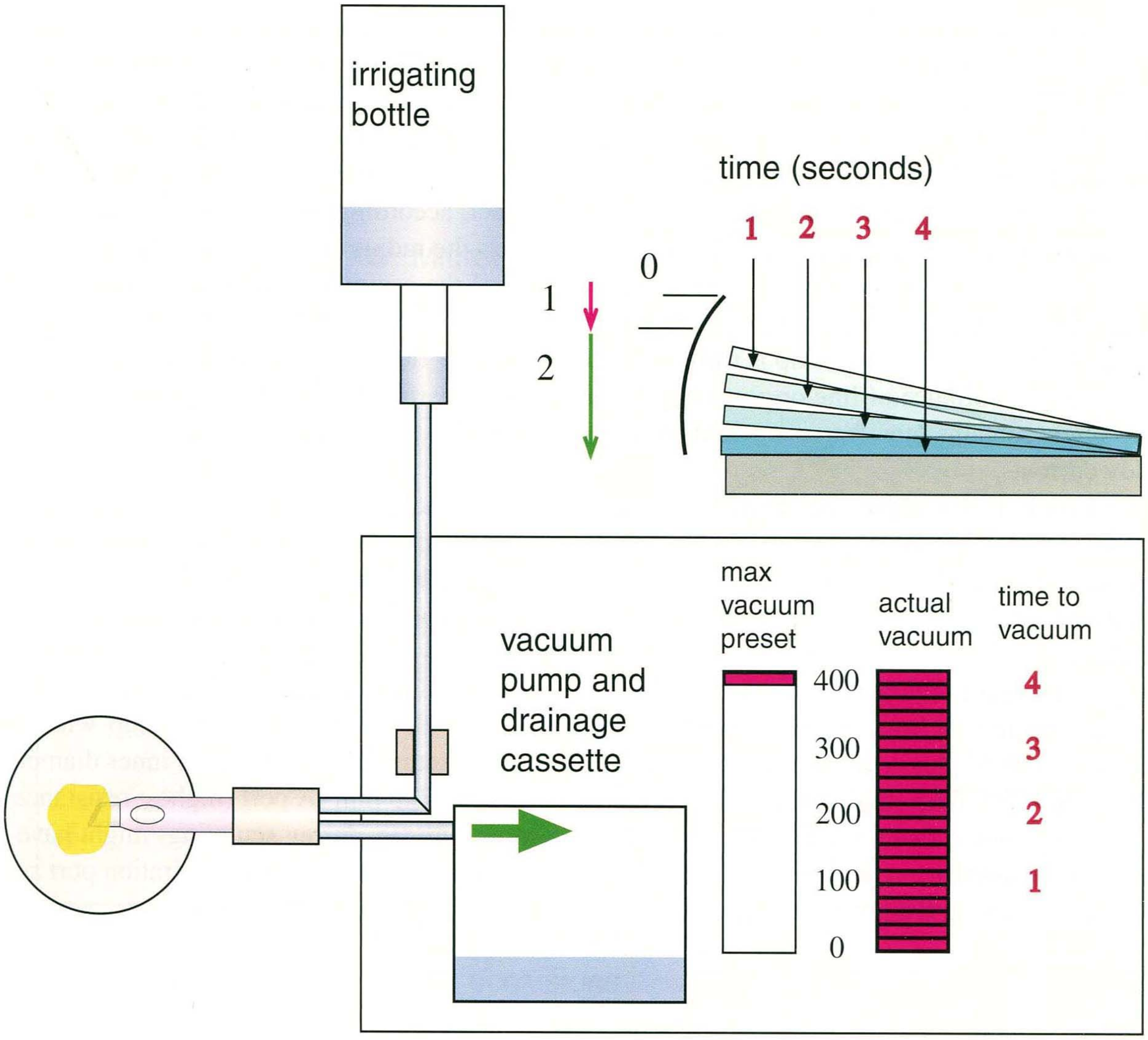

irrigating bottle
time (seconds)
1 2 3 4
0
1
2
vacuum pump and drainage cassette
max vacuum preset
actual vacuum
time to vacuum
400
300
200
100
0
4
3
2
1

FIGURE 1-39

Fluidic Resistors Affecting Flow: Vacuum Pump

As was illustrated in Figure 1-28, the direct linear control of vacuum in the drainage cassette of vacuum pumps allows indirect linear control of flow. However, this indirect flow control means that these pumps are more sensitive than flow pumps to restrictive variances in the fluidic circuit. One component of this "restrictance" (resistance) is the length and internal diameter of the tubing. Another especially important point of resistance is the diameter of the aspiration port, which is usually the smallest diameter of the fluidic circuit. In fact, according to **Poiseuille's Law**, fluidic resistance is proportional to r to the 4th power, where r is the radius of the aspiration port or aspiration line lumen at a given point or section; therefore, if the aspiration port was reduced to half of its original radius, the flow rate through it would be reduced to one sixteenth of the original value. Although this relationship is truly accurate for laminar flow in a viscous fluid, it still underscores the importance of line or port diameter in phacoemulsification, even though the aspiration line often contains lens fragments and viscoelastic globules that produce nonlaminar flow with eddy currents.

Figure 1-40A represents a venturi (vacuum pump) machine with a 24-inch bottle height; when aspiration ports are present, they are unoccluded. The purple data points represent the irrigation line coupled directly to the aspiration line, whereas the other data points represent different fluidic resistors connecting the two lines, such as a phaco handpiece with a test chamber over a standard 19 Ga. phaco tip (green dots). Note how higher vacuums produce higher flow rates (Figure 1-28) for any given handpiece/tubing combination. Also note how the flow rate at a given vacuum decreases from the setup with no handpiece (lowest resistance) to the setup with the 0.9mm standard phaco tip port (medium resistance) to the setup with the 0.5 mm inner diameter MicroFlow phaco tip (higher resistance) to the setup with the 0.5 mm IA port (highest resistance). It should be noted that a partially occluded standard phaco tip (ie, during sculpting) might have a flow profile similar to the MicroFlow or IA tip because of the smaller effective aspiration port surface area resulting from partial occlusion (see the middle diagram in Figure 1-11).

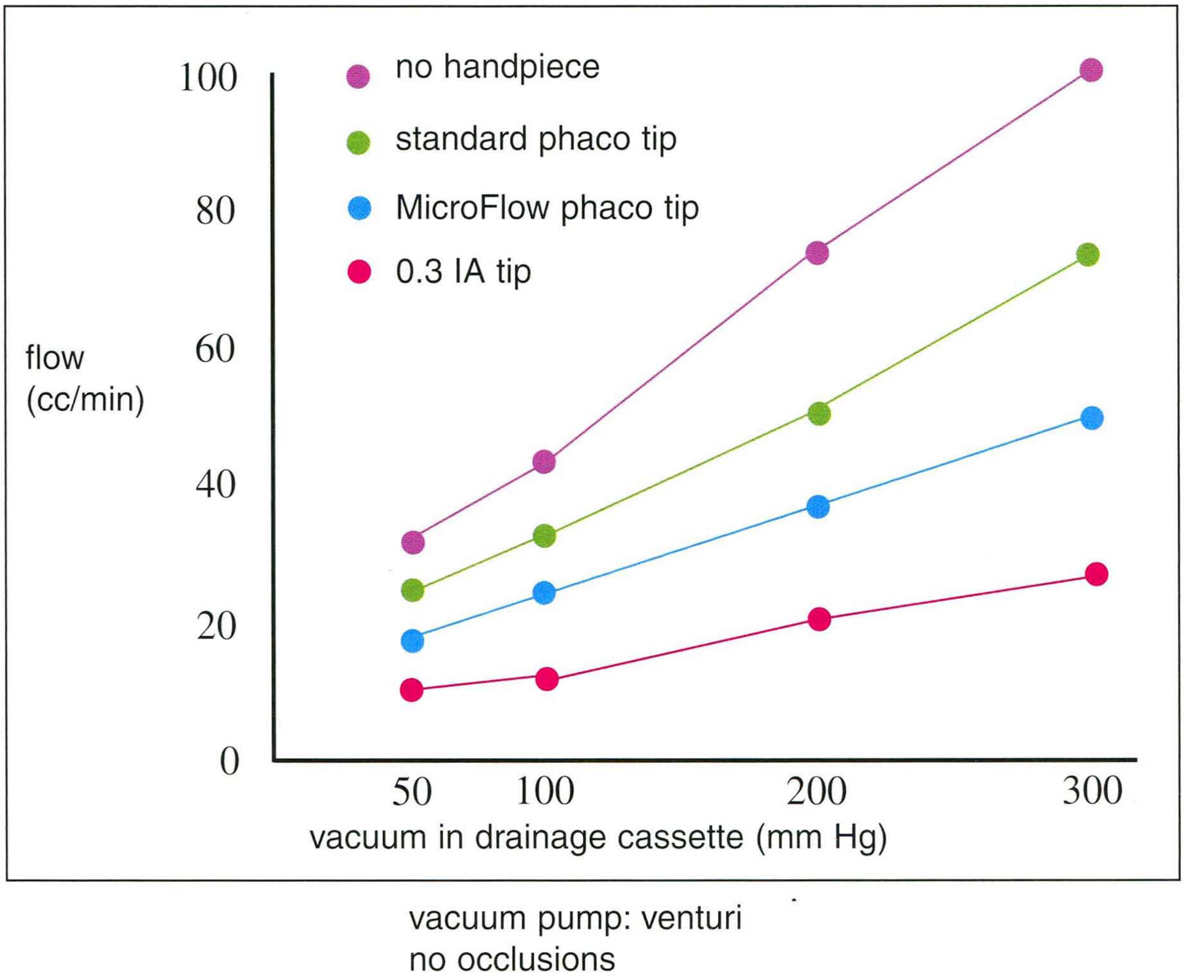

no handpiece
standard phaco tip
MicroFlow phaco tip
0.3 IA tip
flow
(cc/min)
100
80
60
40
20
0
50
100
200
300
vacuum in drainage cassette (mm Hg)
vacuum pump: venturi
no occlusions

FIGURE 1-40A

Fluidic Resistors Affecting Flow: Vacuum Pump vs Flow Pump

Another way to think about this phenomenon is in terms of percentages (Figure 1-40B). For example, if the vacuum and bottle height on a particular venturi machine (without a handpiece) are adjusted to produce 40 cc/min measured outflow in the drainage cassette (purple dot over 100 mm Hg in Figure 1-40A), then adding a phaco handpiece to the fluid circuit will decrease the flow rate to 30 cc/min, a 25% drop (green dot over 100 mm Hg in Figure 1-40A). Similarly, using an IA tip will decrease flow by 70% because of the greater resistance across the 0.3 mm IA port (red dot at 13 cc/min over 100 mm Hg in Figure 1-40A). Note in Figure 1-40B that the same phaco tip and IA tip resistors affect flow less on a peristaltic machine (-5% and -35%, respectively) than they did on the venturi machine.

This phenomenon is simply a reflection of the different nature of the two pumps. The commanded vacuum on a venturi machine (vacuum pump) pulls the aspiration line fluid with a certain amount of **force** to produce 40 cc/min without a handpiece. This same force will pull less volume of fluid per unit time if fluidic resistance is higher (Figure 1-29). However, in order to produce 40 cc/min without a handpiece on a flow pump, the flow rate control commands the pump head to push against the aspiration line tubing with a certain amount of **speed**. As fluidic resistance increases, the pump will exert more force (producing higher vacuum in the aspiration line) in order to maintain the same rotational pump head speed. Notwithstanding any flow losses related to volumetric efficiency, the flow pump will maintain a commanded flow rate better than a vacuum pump with its indirectly commanded flow rate. Bear in mind that if the control feedback algorithm on a flow pump is changed so that it emulates a vacuum pump (Figures 1-32 and 1-33), the resistance effects on flow rate would be identical to those of the venturi machine in Figure 1-40B.

An easy way to observe the effect of resistors on flow is to look at the bottle drip chamber while using pedal position 2 with test chambers on the IA and phaco handpieces (see Figure 1-29). For a given pump speed/strength setting, the drip chamber activity will be greater with the lower resistance phaco tip; remember that the drip chamber activity mirrors the speed and strength of the anterior chamber current.

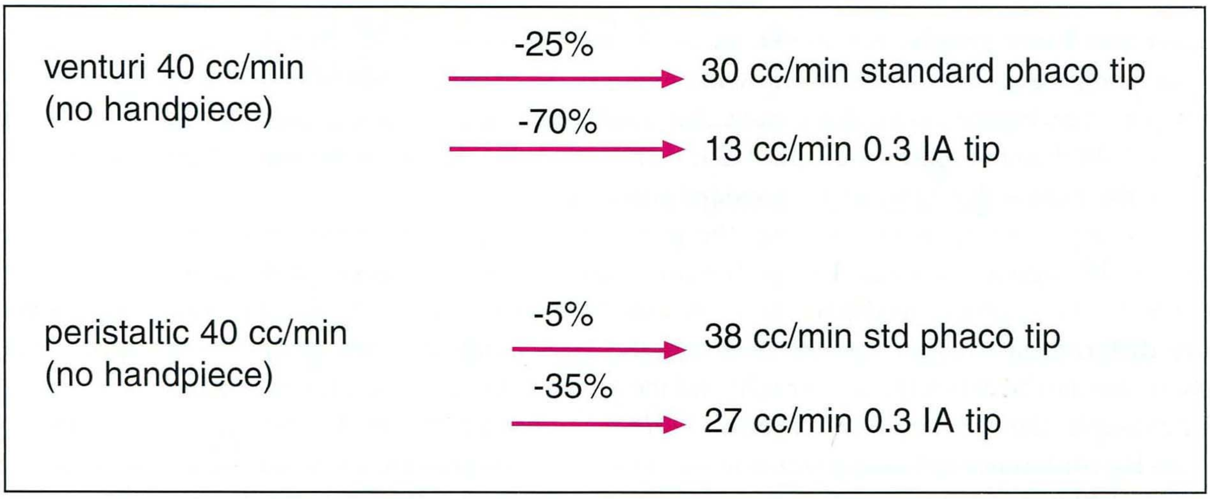

venturi 40 cc/min
(no handpiece)
-25%
30 cc/min standard phaco tip
-70%
13 cc/min 0.3 IA tip
peristaltic 40 cc/min
(no handpiece)
-5%
38 cc/min std phaco tip
-35%
27 cc/min 0.3 IA tip

FIGURE 1-40B

Fluidic Resistors Affecting Vacuum: Flow Pump

Whereas Figure 1-40A illustrated the effect of fluidic resistors on flow given a commanded vacuum with a vacuum pump, Figure 1-41 demonstrates their effect on vacuum at various points in the fluidic circuit given a commanded flow on a **flow pump**. Bottle height is set to 24 inches above the eye (the test chamber where IOP is measured) and the **aspiration port** in each graph is **unoccluded**. The machine's vacuum limit is set to 400 mm Hg and 0 mm Hg on the graph is calibrated to represent ambient atmospheric pressure. **Note the different pressure scales in the upper and lower graphs**. Recall that the commanded flow setting determines the rotational speed of the pump head and that actual flow may be less depending on the size of the effective aspiration port (see Figure 1-11). Also, note that a different phaco machine and tube set was used in Figure 1-41 than in Figures 1-23 and 1-24; therefore, the values are somewhat different when comparing the graphs that represent a standard phaco tip.

At any given flow rate setting, the pump is pulling much harder in trying to draw fluid through the higher resistance IA tip (0.3 mm aspiration port diameter) than the lower resistance standard 19 Ga. phaco needle/tip (0.9 mm aspiration port diameter); note the much larger **pressure differentials** (higher vacuum levels) in the lower graph (IA tip) relative to the upper graph (phaco needle) between the higher IOP and the lower aspiration line pressure at each flow setting. For example, the standard phaco needle at 20 cc/min has a pressure differential of approximately 8 mm Hg (difference between green and red dots) as opposed to the IA tip's differential of approximately 120 mm Hg at the same flow rate. Note also that at any given flow rate, the vacuum in the aspiration line closer to the pump (red dots) is higher (ie, the pressure is lower) than the vacuum level in the aspiration line where it connects to the phaco or IA handpiece (blue dots); this is due to vacuum degradation in the line (see Figure 1-42). Another important aspect of a tip's fluidic resistance is the degree to which flow affects IOP (see Figure 1-6). The IOP (green dots) is seen to be less affected as flow rates increase with the IA tip relative to the standard phaco tip. For example, with the pump speed set for 50 cc/min, the IOP measures 6 mm Hg with the phaco tip but 22 mm Hg with the IA tip (see Figures 1-11 and 1-41). This difference is explained by the fact that the flow rate setting on the graph refers to the commanded rotational pump head speed, which will in turn produce a lower actual flow in the fluidic circuit with a smaller, higher resistance aspiration port (fluidic resistor) (see Figure 1-40B).

The lower diagram using the IA tip in Figure 1-41 also determines which combinations of flow and vacuum are effective and which are counterproductive; please see the discussion with Figure 4-1.

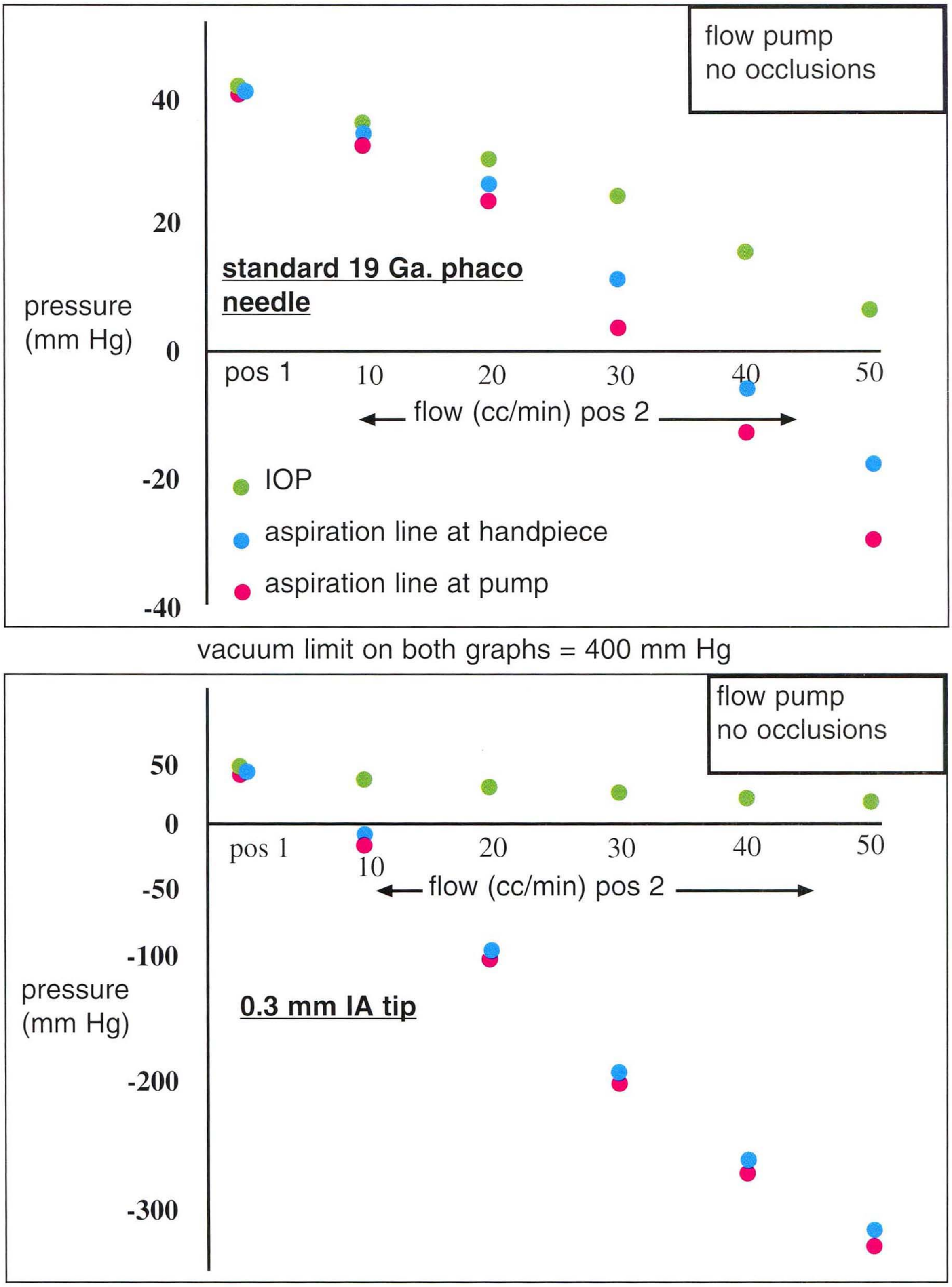

flow pump
no occlusions
40
20
0
-20
-40
pressure
(mm Hg)
standard 19 Ga. phaco needle
pos 1
10
20
30
40
50
flow (cc/min) pos 2
IOP
aspiration line at handpiece
aspiration line at pump
vacuum limit on both graphs = 400 mm Hg
flow pump
no occlusions
50
0
-50
-100
-200
-300
pressure
(mm Hg)
0.3 mm IA tip
pos 1
10
20
30
40
50
flow (cc/min) pos 2

FIGURE 1-41

Vacuum Degradation in Aspiration Line

The actual vacuum readout on the phaco machine is derived from the fluidic circuit's pressure transducer, which is located at or near the pump. However, although this is an accurate reading for this location, the vacuum can be noted to degrade as the distance along the aspiration line from the pump to the unoccluded aspiration port is increased (Figure 1-42). This figure incorporates either a **flow pump operating in vacuum mode** (see Figure 1-32) **or** a **vacuum pump** (Figure 1-28); it illustrates **unoccluded flow** with a MicroFlow tip at various commanded vacuum levels with **additional pressure transducers at locations 1 through 4**. **Location 1** is measured at the connection between the aspiration line and the drainage cassette. **Location 2** is 24 inches away from the cassette, while **location 3** is 48 inches away. **Location 4** is at the other end of the aspiration line where it connects to the phaco handpiece. The graph illustrates vacuum degradation; for example, a commanded vacuum that produces 250 mm Hg at the cassette (green dots) and on the machine readout, but results in only 150 mm Hg vacuum measured at location 4, represents a 100 mm Hg vacuum drop (-100 mm Hg on the graph). **Recall that this graph represents unoccluded flow and that upon occlusion, vacuum transfers from the cassette along the aspiration line to the occlusion at the aspiration port so that all locations would have the same vacuum value as the cassette (see Figure 1-30).**

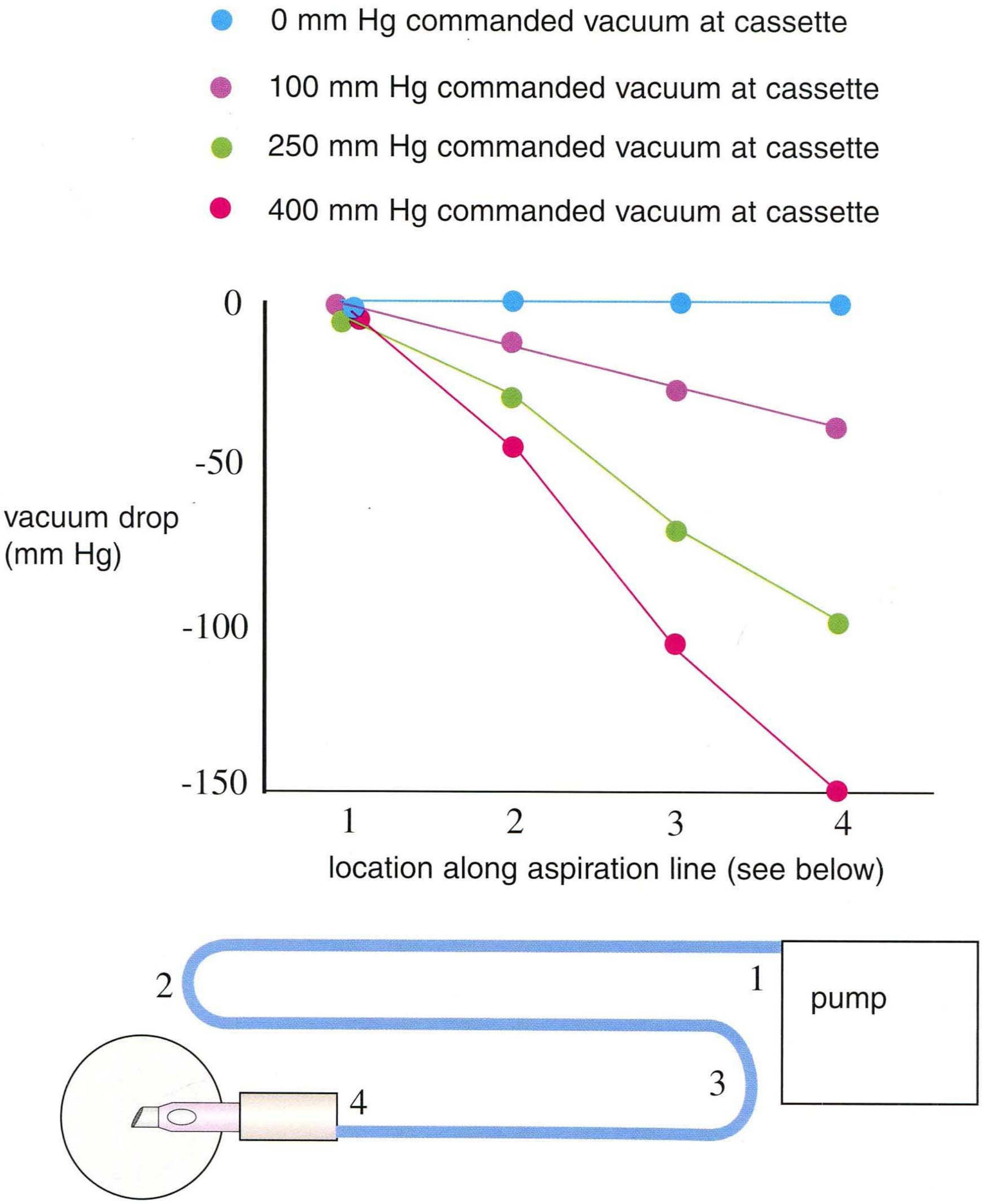

0 mm Hg commanded vacuum at cassette
100 mm Hg commanded vacuum at cassette
250 mm Hg commanded vacuum at cassette
400 mm Hg commanded vacuum at cassette
0
-50
-100
-150
vacuum drop
(mm Hg)
1
2
3
4
location along aspiration line (see below)
2
1
pump
3
4

FIGURE 1-42

Bottle Height: Relationship to Flow

Basically, adjusting the bottle height proportionately adjusts the anterior chamber depth. More specifically, the function of proper bottle height is to produce an adequate IOP, which will maintain the anterior chamber despite aspiration outflow as well as any surges or incisional drainage. Higher flow rates require higher bottle heights to maintain the same IOP as when using lower flow rates. Conversely, lower bottle heights (ie, useful for lowering IOP for such conditions as a small posterior capsule tear) require a correspondingly lower flow rate in order to prevent anterior chamber shallowing and potential collapse. Therefore, bottle height needs to be adjusted dynamically (ie, with an unoccluded aspiration port and active pump function) in foot pedal position 2 or 3. When adjusting bottle height for a given flow rate setting, it is helpful to know if the height adjustment itself affects flow rate. The effect of bottle height on flow is entirely dependent on the type of pump in question. Because flow is constrained at the point where the aspiration line is first interdigitated by a peristaltic pump roller or a scroll element, changing bottle height has no effect on flow with these flow pump machines. In essence, the pump head is acting as a **flow regulator**; despite increased pressure from an increased bottle height, flow cannot proceed any faster than the speed of the pump element traversing the fluid in the aspiration tubing.

On a vacuum pump with an unoccluded aspiration port, however, there is open communication without restriction between the irrigation bottle and the drainage chamber in positions 2 and 3. Therefore, increasing bottle height with resultant increased IOP produces higher flow rates by pushing fluid harder through the aspiration line and into the drainage chamber. By corollary, a given increase in bottle height on a vacuum pump will not produce as much of an increase in IOP as with a flow pump because part of the increased pressure head is dissipated in the faster flow rate with the vacuum pump.

In Figure 1-43, both the flow and vacuum machines were set up to produce a measured 30 cc/min outflow at 24 inches of bottle height; aspiration and irrigation tubing was simply connected without a handpiece. Outflow was then measured at bottle heights of 12 and 48 inches. It can be seen that the peristaltic machine's flow rate was unaffected by the bottle height changes, whereas the venturi machine's flow rate changed proportionately to the bottle height change. Clinically, it is important to realize when flow rate is being increased so that you can anticipate the resultant faster anterior chamber current and stronger attraction of intraocular material to the aspiration port.

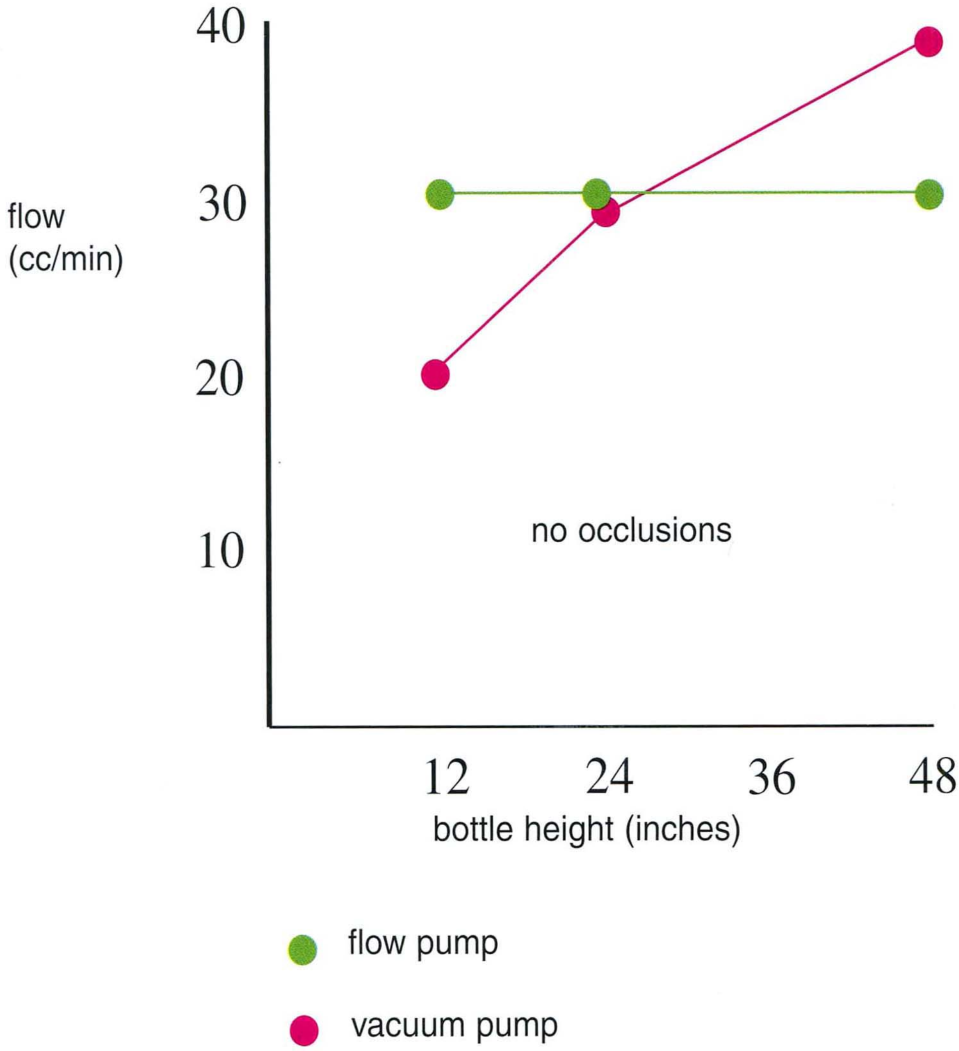
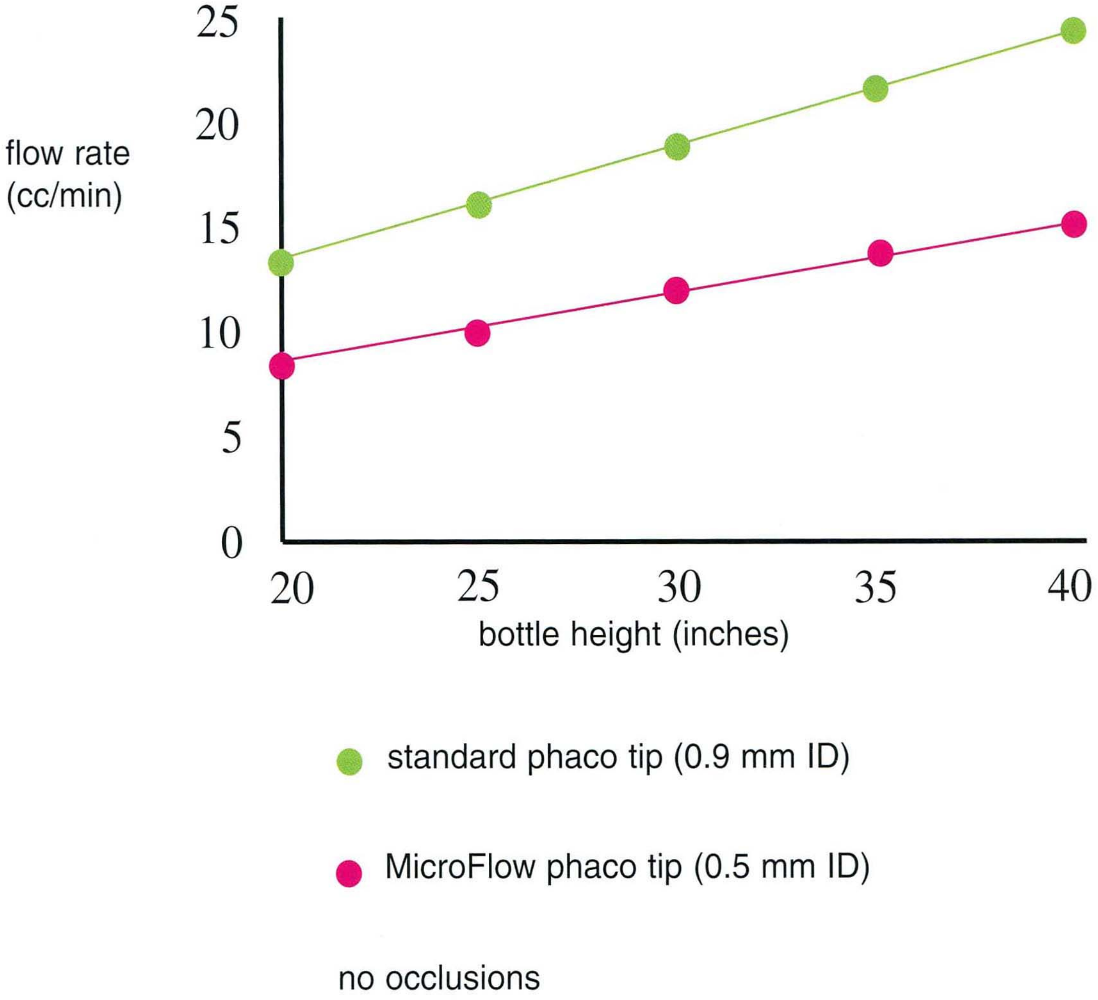

40
30
20
10
flow
(cc/min)
no occlusions
12
24
36
48
bottle height (inches)
flow pump
vacuum pump

Figure 1-43

Baseline Resistance to Flow

In order to further understand the relationship between bottle height and flow with respect to different types of pumps, it is helpful to look at the relation of flow to bottle height without any pump in the fluidic circuit (Figure 1-44). In these cases, the aspiration line is disconnected from the pump and left open to atmospheric pressure at the same height as the phaco handpiece and tip. The pressure head from the elevated irrigating bottle (approximately 11 mm Hg above ambient atmospheric pressure for every 6 inches of bottle height above the phaco tip) drives fluid through the tube set against the resistances of its various components, including the length and **internal diameter (ID)** of the irrigation line, irrigation sleeve, phaco tip, phaco handpiece, and the aspiration line. The point of greatest resistance in the fluidic circuit is typically the point of minimum ID, usually found in the phaco (or IA) tip (recall Poiseuille's Law discussed with Figure 1-40A). As expected, flow increases as bottle height increases; a stronger pressure head drives fluid through the circuit more quickly. However, note that for a given bottle height that the flow rate decreases when going from a standard phaco tip (0.9 mm ID) to a higher resistance MicroFlow tip with its smaller 0.5 mm ID; this same type of flow modulation by fluidic resistance was noted in Figure 1-40A with vacuum used as a pulling force to induce flow as opposed to Figure 1-44 that simply uses bottle height as a pushing force to induce flow.



25
20
15
10
5
0
flow rate
(cc/min)
20
25
30
35
40
bottle height (inches)
standard phaco tip (0.9 mm ID)
MicroFlow phaco tip (0.5 mm ID)
no occlusions

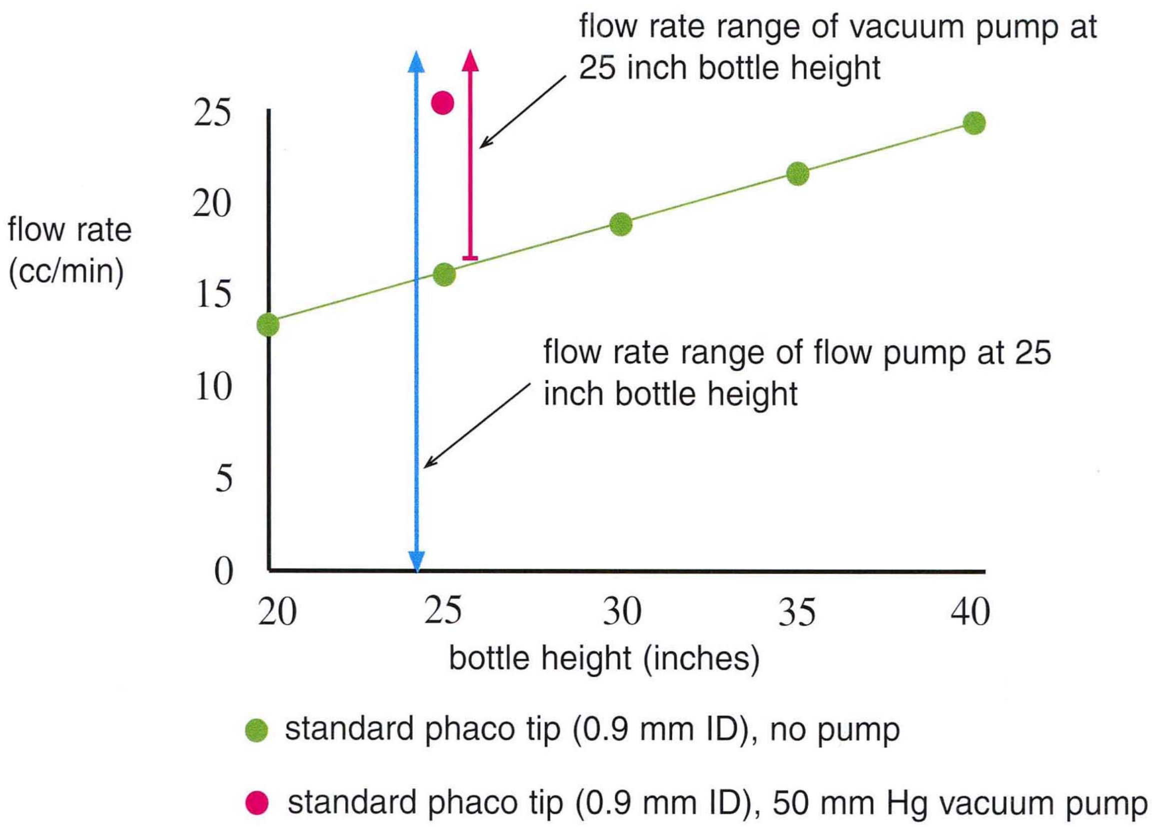
FIGURE 1-44

Flow Control: Vacuum vs Flow Pumps

Figure 1-44 described a fluidic circuit without a pump. If the aspiration line is now reconnected to an active vacuum pump, it will increase the flow rate (in position 2 or 3) for any given bottle height. The reasoning is as follows: the flow vs bottle height graph in Figure 1-44 had the aspiration line disconnected from the pump and left open to atmospheric pressure; this pressure is considered to be zero (ie, neither above or below ambient atmospheric pressure, see Appendix C). The active vacuum pump produces vacuum (negative pressure, below ambient atmospheric) in the drainage cassette. Note that the vacuum is by convention expressed by a positive number in mm Hg even though it represents a negative value relative to atmospheric pressure. When the aspiration line is reconnected to this active drainage cassette, the pressure differential between the irrigating bottle and the fluidic circuit drain is increased, thereby increasing the driving force of the circuit as the vacuum pulls on the aspiration line fluid with a force that is additive to that of the irrigating bottle that is pushing the aspiration line fluid.

Note that because a vacuum pump works by producing vacuum at the end of the fluidic circuit, it can only increase the circuit's pressure differential, thereby increasing flow over the baseline level without the pump (see red arrow in Figure 1-45). However, a flow pump can not only raise but also lower the flow rate at any given bottle height because the interdigitation of the pump element within the fluid circuit allows it to act as a **flow regulator** (see blue arrow in Figure 1-45). The irrigating bottle pressure head cannot drive the fluid any faster than the pump head's rotation; therefore, flow rates below the green baseline (no pump) level can be achieved (see Figures 1-10-3 and 1-45). For flow rates above the baseline level, the flow pump acts exactly the same as a vacuum pump in that it pulls on the fluidic circuit with induced vacuum which increases the pressure differential and thereby increases flow; a given amount of induced vacuum will produce the same incremental increase in flow regardless of whether a flow pump or a vacuum pump produced the vacuum (see also Figure 1-33).

Note that in the derivation at the bottom of Figure 1-45 that the relationship of 11 mm Hg per 15 cm of bottle height (Appendix C) has been rounded off to 10 mm Hg per 15 cm of bottle height. The additional force provided by the pump increases the baseline flow accordingly (red dot).



bottle height 25 inches is approximately 60 cm

60 cm x (10 mm Hg / 15 cm bottle height) = 40 mm Hg

For a fluidic circuit without a pump, the pressure differential within the circuit is the 40 mm Hg positive pressure head from the irrigating bottle minus the pressure at the end of the open aspiration line (zero relative to ambient atmospheric pressure).
40 mm Hg - 0 mm Hg = 40 mm Hg

For a fluidic circuit with a pump/drainage cassette vacuum of 50 mm Hg (ie, 50 mm Hg below atmospheric), the pressure differential within the circuit is:
40 mm Hg - (-50) mm Hg = (40 + 50) mm Hg = 90 mm Hg

FIGURE 1-45

Compliance and Air Venting

Although compliance and venting have previously been discussed separately (see Figure 1-14), it is useful to examine the relationship between them. Recall that venting mechanisms function by neutralizing aspiration line vacuum between the pump (either vacuum or flow pump) and an occlusion at the handpiece's aspiration port; venting also prevents a rotating flow pump from building vacuum past the vacuum limit preset. For example, Figure 1-46-1 shows a large nuclear fragment impaled by the phaco tip up to the silicone sleeve, which prevents further boring into the fragment. The fragment should be released so that it can be reengaged in a more effective carouseling configuration (see Figure 3-36); however, its release is inhibited by vacuum that has built up in the aspiration line between the pump roller pinching off the line at one end and the occlusion at the other end. Even when the foot pedal is released to position 1 or 0 (thereby stopping aspiration flow and pump head rotation), the vacuum will remain unless air or fluid is vented into the aspiration line to equilibrate the pressure with that of the anterior chamber/irrigation line. Therefore, most modern phaco machines automatically engage a venting mechanism when the foot pedal is raised from position 2 into position 1 or 0. Note that venting aspiration line pressure to 0 may by itself be insufficient for releasing the engaged nuclear fragment, which may require refluxing (Figure 1-4) and/or manipulation with a second instrument through the paracentesis.

Venting air into the line (ie, venting to atmospheric pressure) can potentially decrease the efficiency of the pump because of air's high compliance. When attempting to rebuild vacuum after reengaging the fragment, the pump must first overcome the air's compliance by stretching it before vacuum effectively builds in the aspiration line fluid, thereby contributing to a **rise time lag**. Figure 1-46-2 shows the system just after it has reengaged the fragment which was released from its previous position in Figure 1-46-1 by venting air into the aspiration line; note the residual air bubble at the end of the vent tube. As the pump starts to turn, the highly compliant bubble expands its volume with relatively little effort by the pump (note the minimal increase in vacuum between Figures 1-46-2 and 1-46-3). Vacuum starts to significantly build in Figure 1-46-4 only after the air bubble has been fully stretched to the limit of its compliance, and the pump then begins to act on the fluid in the aspiration line; note the effect of the increased vacuum which draws the fragment more strongly onto the tip (aided by light ultrasound power) into a much more favorable tangential engagement as opposed to Figure 1-46-1 (see also Figure 3-36 for a discussion of the importance of tangential engagement of carouseling fragments).

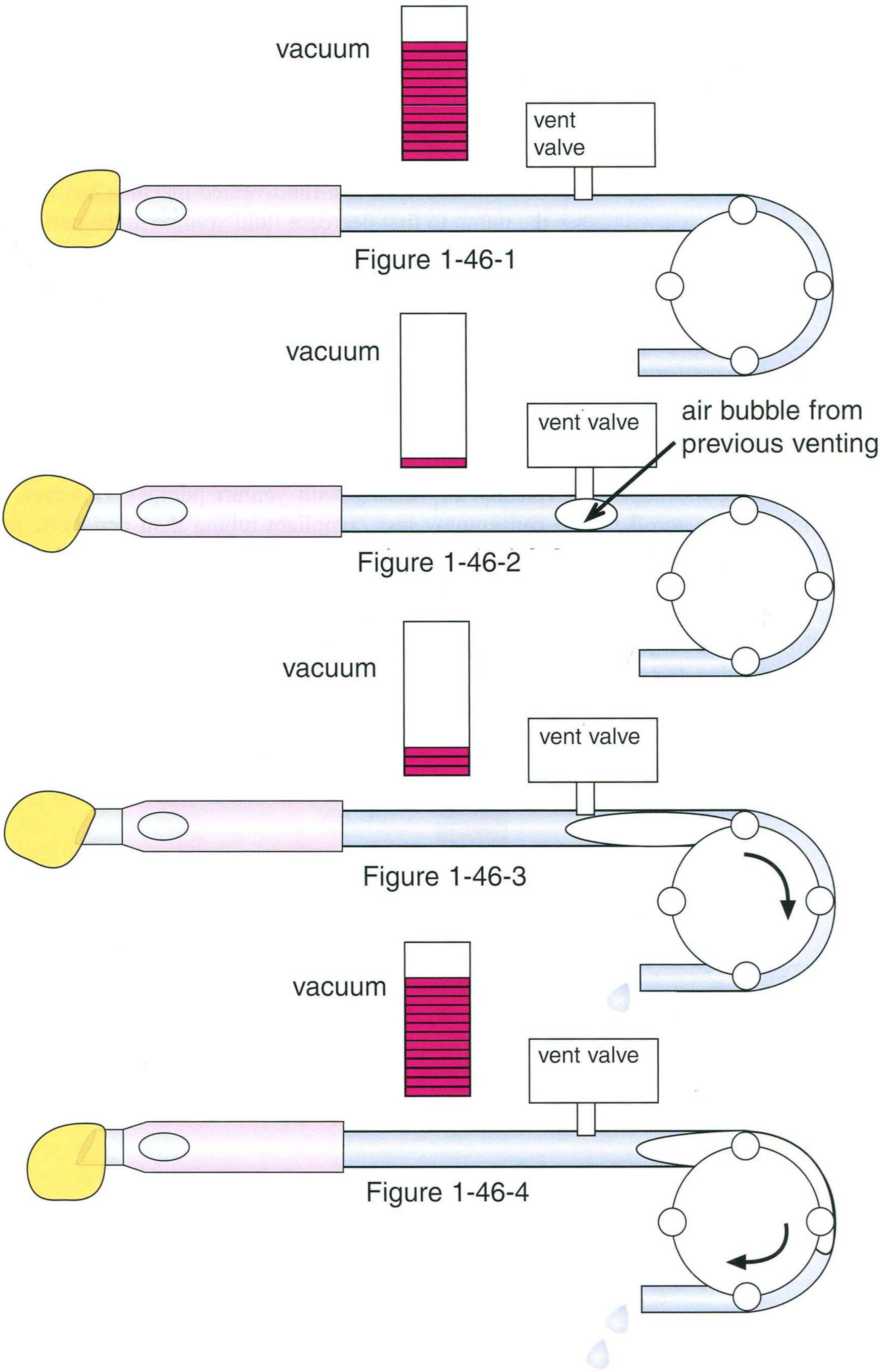

vacuum
vent valve
Figure 1-46-1
vacuum
vent valve
air bubble from previous venting
Figure 1-46-2
vacuum
vent valve
Figure 1-46-3
vacuum
vent valve
Figure 1-46-4

FIGURE 1-46

Compliance and Fluid Venting

The venting system is not the only determinant of a machine's compliance; **aspiration line compliance** also plays an important role. For example, if a fluid-vented machine has very compliant tubing, an occlusion will cause the pump to first decrease fluid volume in the partially collapsing line before effectively building vacuum (see blue arrows in the middle diagram of Figure 1-47); this will lead to longer rise times. Recall how this effect can be diminished in flow pumps with bicompliant tubing as discussed with Figures 1-9 and 1-14. Note that the fluid bolus which had previously been vented into this system has not decreased the system's compliance; even though it deforms to conform to the collapsing tubing's dimensions (Figure 1-47, middle and bottom diagrams), its volume has not changed (contrast this to the air bolus in Figures 1-46-2 through 1-46-4).

Although a flow pump is used in these illustrations, it should be noted that vacuum pumps also employ venting mechanisms (typically air venting with venturi pumps). However, these pumps (along with the scroll pump) can employ less compliant tubing than peristaltic pumps because the latter must be able to completely collapse the tubing with the pump head rollers in order for the pump to function. Also, rise time lags due to air venting in vacuum pumps are typically not as much of a liability because these pumps (especially venturi) inherently build vacuum faster than flow pumps (especially peristaltic); any induced rise time lag is usually minimal and negligible. If deemed undesirable, these inherently fast rise times can be attenuated with some vacuum pumps as desired by the surgeon as discussed in Figure 1-35.

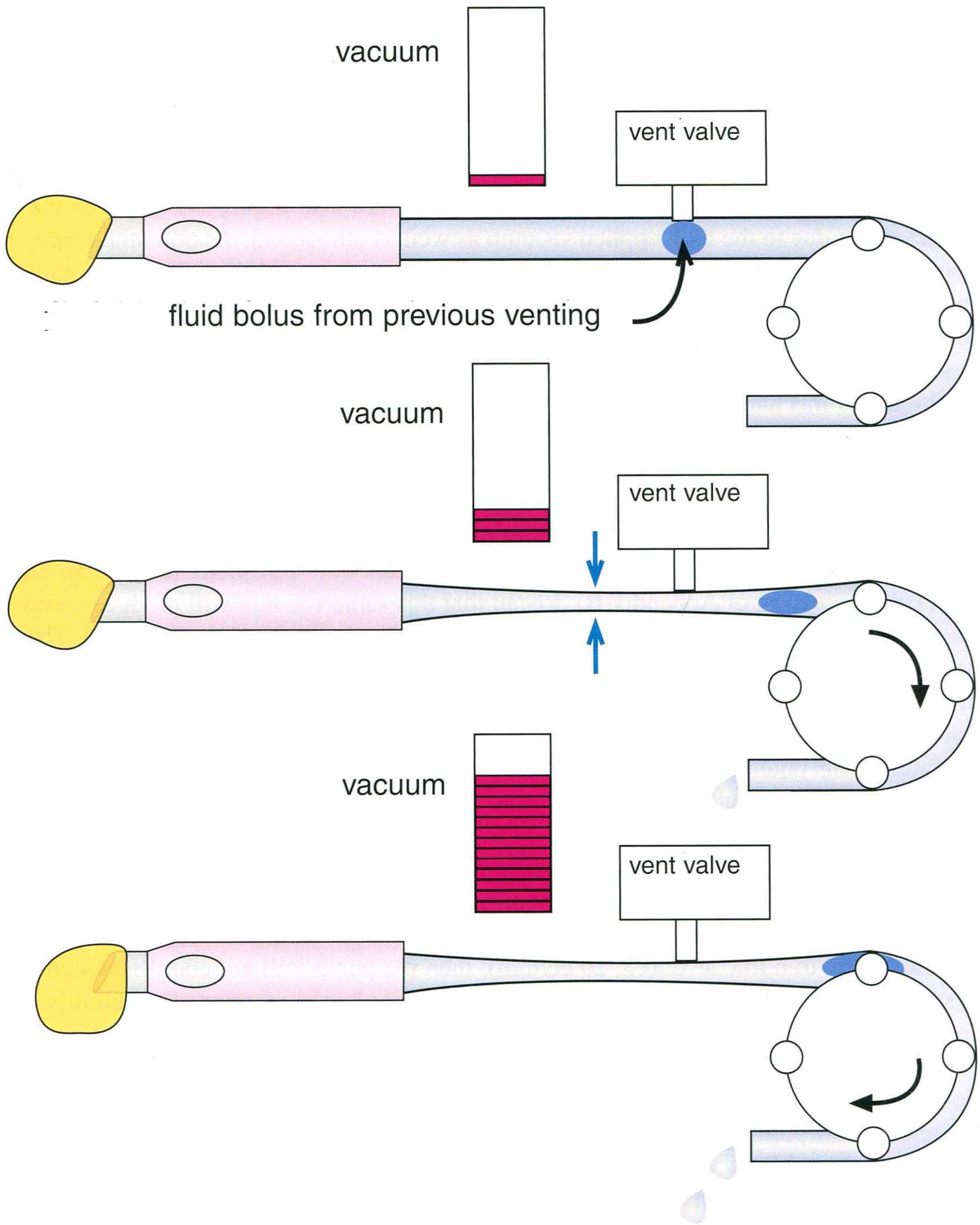

vacuum
vent valve
fluid bolus from previous venting
vacuum
vent valve
vacuum
vent valve

FIGURE 1-47

Surge

Postocclusion surge is a phenomenon that occurs when vacuum builds to high levels between the machine pump and an occlusion at the aspiration port. The high vacuum levels can pull out and expand air bubbles from the aspiration line fluid. The high vacuum also partially collapses the aspiration line tubing (Figure 1-48-1), with the change in tubing volume divided by the change in applied vacuum being defined as **compliance** (see also Figure 1-14). When the occlusion breaks down due to the high applied vacuum as well as ultrasound, the potential energy of the re-expanding tubing and collapsing air bubbles adds momentary additional outflow pull to the flow which had been previously been balanced to the current bottle height at a steady state condition; therefore, the chamber may briefly shallow, dimple, or even collapse if the additional outflow is excessive (Figure 1-48-2). Needless to say, this collapse could cause damage to the cornea or capsule by direct mechanical contact with the phaco needle. In addition to compliance, surge is dependent on the pre-surge vacuum level, as well as the resistance in the irrigation and aspiration portions of the fluid circuit, along with the fluidic circuit's supply pressure head as determined by the irrigating bottle's height.

Surge potential is also influenced by the pump type and setting. For example, a vacuum pump with a level of 200 mm Hg will produce a certain amount of gripping force of an occluded fragment (see discussion of Appendix B). Recall that this same vacuum will produce a very rapid flow rate with an unoccluded standard phaco tip (about 50 cc/min as in Figure 1-40A). Therefore, at the moment of an occlusion break with this setup, the surge due to compliance equilibration will be intensified by a rapid flow rate corresponding to the high vacuum setting; recall how a faster flow rate decreases IOP through Bernoulli's equation (Figures 1-6-2 and 1-10A). The surgeon can compensate for this potential problem by titrating vacuum dynamically (with linear pedal control) during the procedure so that high levels are used only when needed during aspiration port occlusion (see also discussion of Figure 2-16B).

A flow pump can deal with this issue differently because of the ability to independently set the parameters of vacuum and flow. For example, a flow pump with a vacuum preset of 200 mm Hg can grip a fragment with the same force as a vacuum pump with the same setting. However, if the flow rate is set to a low level (eg, 20 cc/min), then the pump will not contribute significantly to the surge during an occlusion break relative to the previously mentioned vacuum pump (50 cc/min produced on occlusion break with a vacuum setting of 200 mm Hg). Unfortunately, this safer, slow flow setting (ie, slow rotational pump head speed) will result in possibly unsatisfactorily slow rise times when dealing with these higher vacuum levels. Furthermore, this theoretical advantage of a flow pump with regard to surge control is offset by its need to use more compliant tubing than is needed by a vacuum pump; increased fluidic circuit compliance tends to lead to more surge potential, especially in machines without bicompliant tubing (see Figure 1-47).

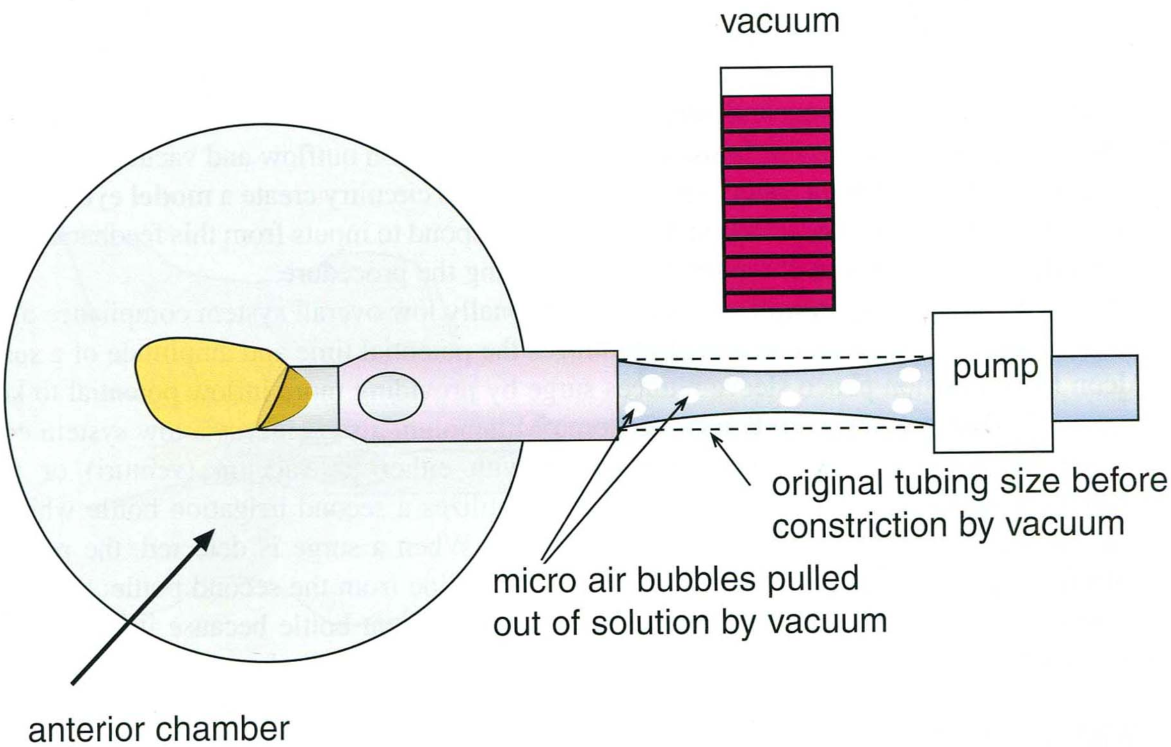

vacuum
pump
original tubing size before constriction by vacuum
micro air bubbles pulled out of solution by vacuum
anterior chamber

FIGURE 1-48-1

Surge (continued)

Surge control has been dealt with in a variety of ways by different manufacturers. Fluidic circuits should be engineered with minimal compliance which will still allow adequate ergonomic manipulation of the tubing/handpiece as well as functioning of the pump mechanism, the latter being primarily important for peristaltic pumps. Small bore (internal diameter) aspiration line tubing, utilized by AMO and Alcon, provides increased fluidic resistance which obtunds surges (see Figure 1-40A for the principle behind this). Most modern peristaltic pumps logarithmically decrease pump speed as the actual vacuum approaches the maximum vacuum preset. When the pressure transducer senses an occlusion break, the pump speed is increased again logarithmically rather than abruptly in order to minimize the amount of aspiration outflow and vacuum that needs equilibration by venting. The pressure transducer and related circuitry create a **model eye** that mirrors IOP and therefore chamber stability; the machines respond to inputs from this feedback mechanism in order to limit anterior chamber instability during the procedure.

The Alcon Legacy and Infiniti utilize an exceptionally low overall system compliance along with a low resistance irrigation line which minimizes the potential time and amplitude of a surge. The Alcon High Infusion phaco sleeve reduces surge by providing more inflow potential to keep the anterior chamber formed. The Bausch & Lomb Millennium also achieves a low system compliance via the use of lower compliance tubing with either its vacuum (venturi) or flow (Concentrix) modules. The Surgical Design machine utilizes a second irrigation bottle which is raised a few inches above the primary irrigation bottle. When a surge is detected, the pump is momentarily stopped as fluid is vented into the aspiration line from the second bottle; aspiration line vacuum is preferentially equilibrated by fluid from this vent bottle because it has a higher pressure than the anterior chamber, which has the same pressure as the lower primary irrigation bottle.

While all of these designs are helpful, it is ultimately up to the surgeon to set parameters which optimize a given machine for a given patient with regard to surge prevention. **When observing surge**, the surgeon's **first** response should be to **raise the bottle height** to provide additional inflow pressure to better keep up with the observed excess outflow rate. If this adjustment is inadequate, then the **second** response should be to **lower the vacuum level**. Ideally, high vacuum would be used only when the aspiration port is solidly occluded, such as during the stabilization of the nucleus when chopping; then, if the surgeon is using Dual Linear Control, the vacuum may lowered to more appropriate level for carouseling phacoaspiration of the chopped fragment, during which occlusion breaks will be expected (Figure 2-16B). Other options include changing to a more resistive phaco needle (eg, Bausch & Lomb MicroFlow or Alcon Flare Tip) or a more resistive tubing set (eg, Alcon MaxVac); inflow can be augmented by such devices as the Alcon High Infusion Sleeve or an anterior chamber maintainer (Figure 1-2). Needless to say, these latter choices of hardware are ideally made prior to a case rather than in the middle of one.

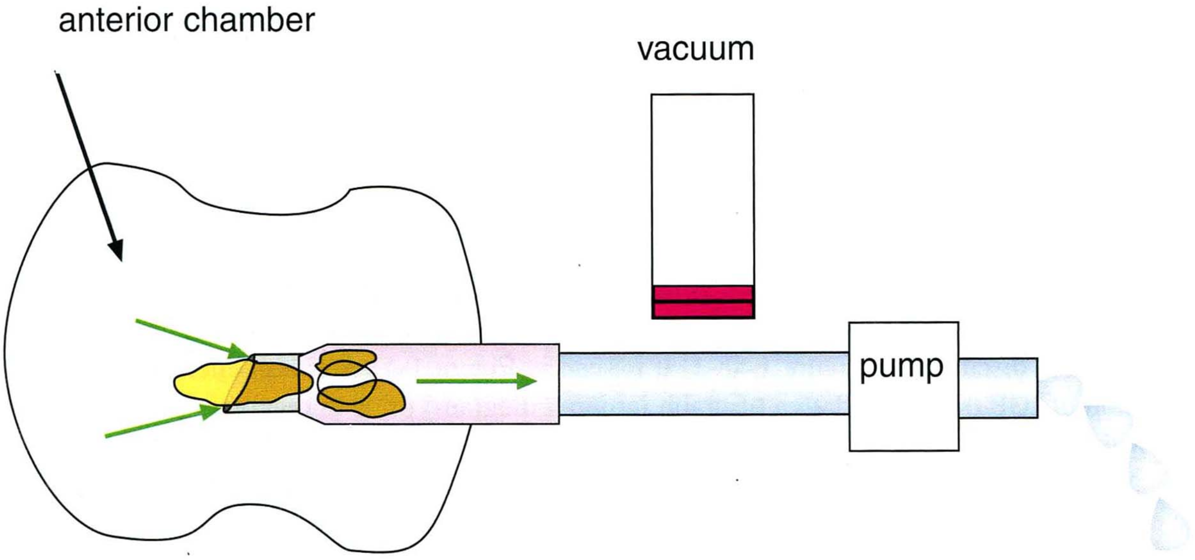


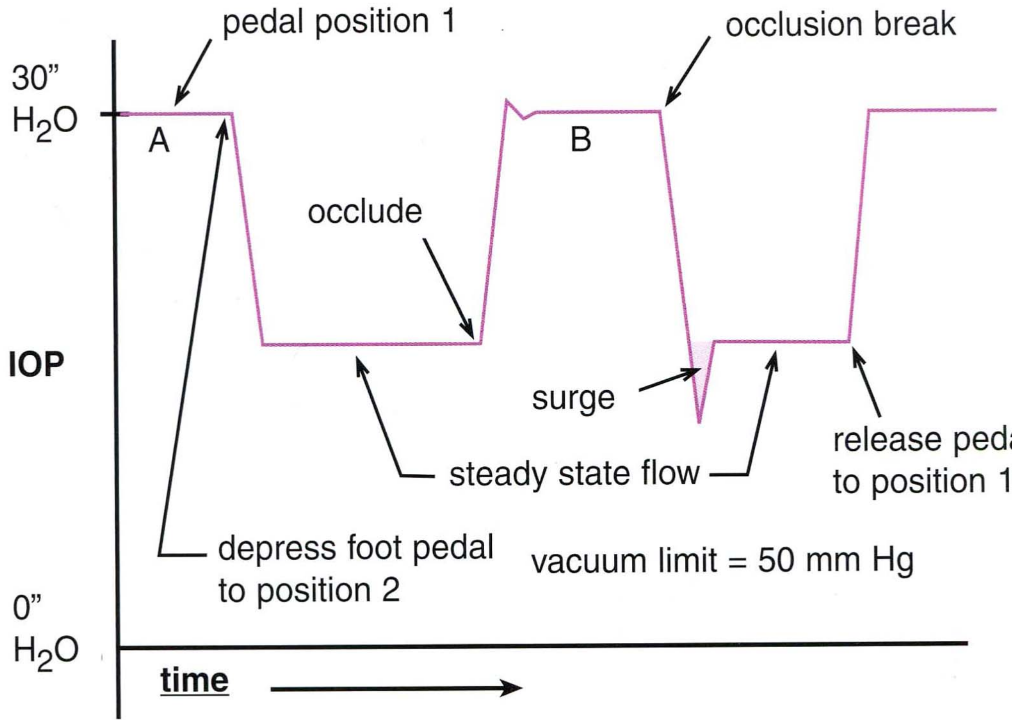
FIGURE 1-48-2

Surge (continued)

Another way to look at surge is by **graphing IOP** (intraocular pressure) as shown in **Figure 1-48-3**. In this setup (utilizing a **flow pump machine**), the flow rate is 30 cc/min, a standard tube set and needle are used, and occlusions are created and released with a stopcock which connects the aspiration line to the phaco handpiece. The bottle height is 30 inches above the test chamber, which was downsized to approximate the volume of the human anterior chamber; this bottle height produces a **hydrostatic IOP of 30 inches of water (or approximately 55 mm Hg)** in foot pedal position 1; recall that these pressures are relative to atmospheric pressure, which is set as zero (either inches H_2O or mm Hg) on the graph. When position 2 is engaged, pump action causes flow through the fluidic circuit which decreases the IOP to a steady state level as long as the pump speed is maintained and the tip is unoccluded (see also Figure 1-6). With sudden occlusion of the aspiration port, the IOP returns to 55 mm Hg (see also Figure 1-7, noting the different bottle height and consequently different IOP versus Figure 1-48-3). However, even though the IOPs are equivalent in segments A and B of the upper graph, the aspiration line pressure (ALP) is equal to the IOP in segment A, whereas in segment B the ALP reaches the vacuum limit preset of 50 mm Hg vacuum, or -50 mm Hg pressure (see also Figure 1-24). Upon occlusion break, surge is produced by the factors discussed in Figure 1-48-1. It is seen in Figure 1-43-3 as a momentary downward deflection of IOP (see shaded area of graph in upper diagram) prior to regaining the IOP associated with steady state flow.

Note the lower diagram of Figure 1-48-3 in which higher vacuum limits are depicted to show the effect on surge of varying this parameter relative to the 50 mm Hg limit used in the upper diagram as discussed in the preceding paragraph. A higher vacuum creates a greater change in volume in the aspiration line upon occlusion (eg, larger air bubbles and more tubing constriction per Figure 1-48-1), which produces a greater reactive equilibration on occlusion break. As the vacuum limit preset is increased, the amplitude and time duration of surge proportionately increases (note the progressively larger shaded areas). Correspondingly, the anterior chamber proportionately shallows as surge drives the IOP lower for more time duration. In particular, note that for vacuum limits of 160 and 250 mm Hg, the surge drives the IOP below zero (atmospheric pressure), with the higher preset value maintaining this pressure for a longer time (larger shaded area below zero pressure) with a proportionately greater likelihood of anterior chamber collapse.

Higher vacuum limit presets therefore pose a significant danger of anterior chamber collapse. Surgeons must watch for warning signs of momentary anterior chamber shallowing when an occlusion abruptly clears (eg, when chopping or carouseling); if noted, one should compensate by using a higher bottle height, a more restrictive tubing/needle combination, or a lower vacuum limit preset. Although flow rate could also be lowered, this parameter more directly affects the IOP during steady state unoccluded flow than the amount of transient surge.


pedal position 1
occlusion break
30" H_2O
A
B
occlude
IOP
surge
steady state flow
release pedal to position 1
depress foot pedal to position 2
vacuum limit = 50 mm Hg
0" H_2O
time

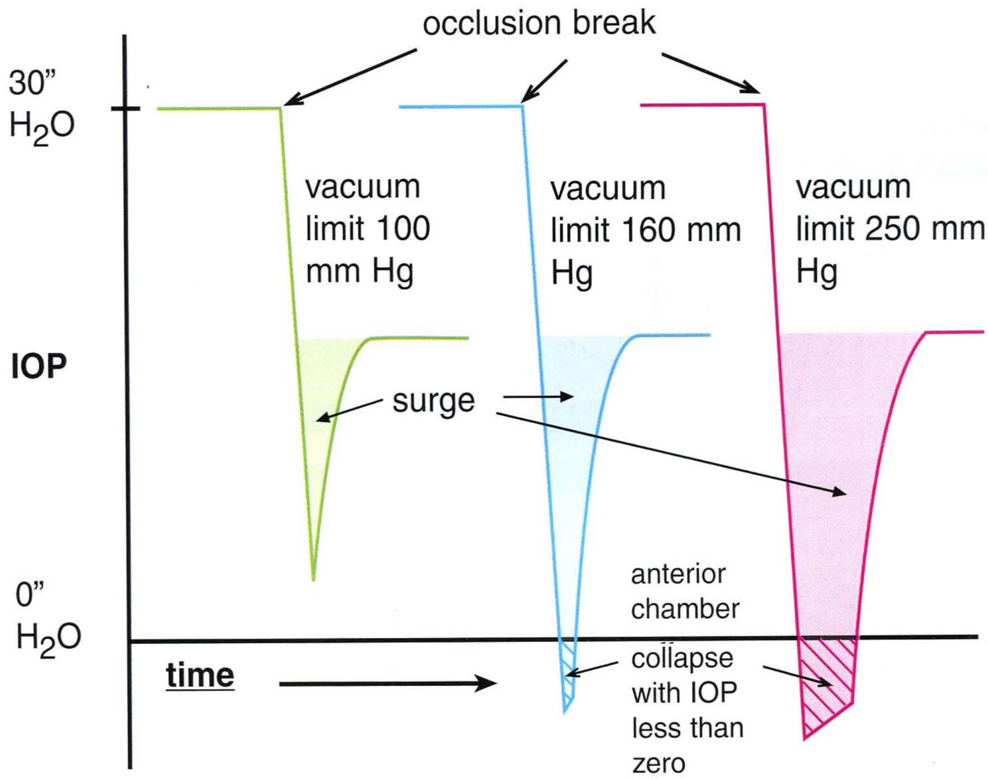
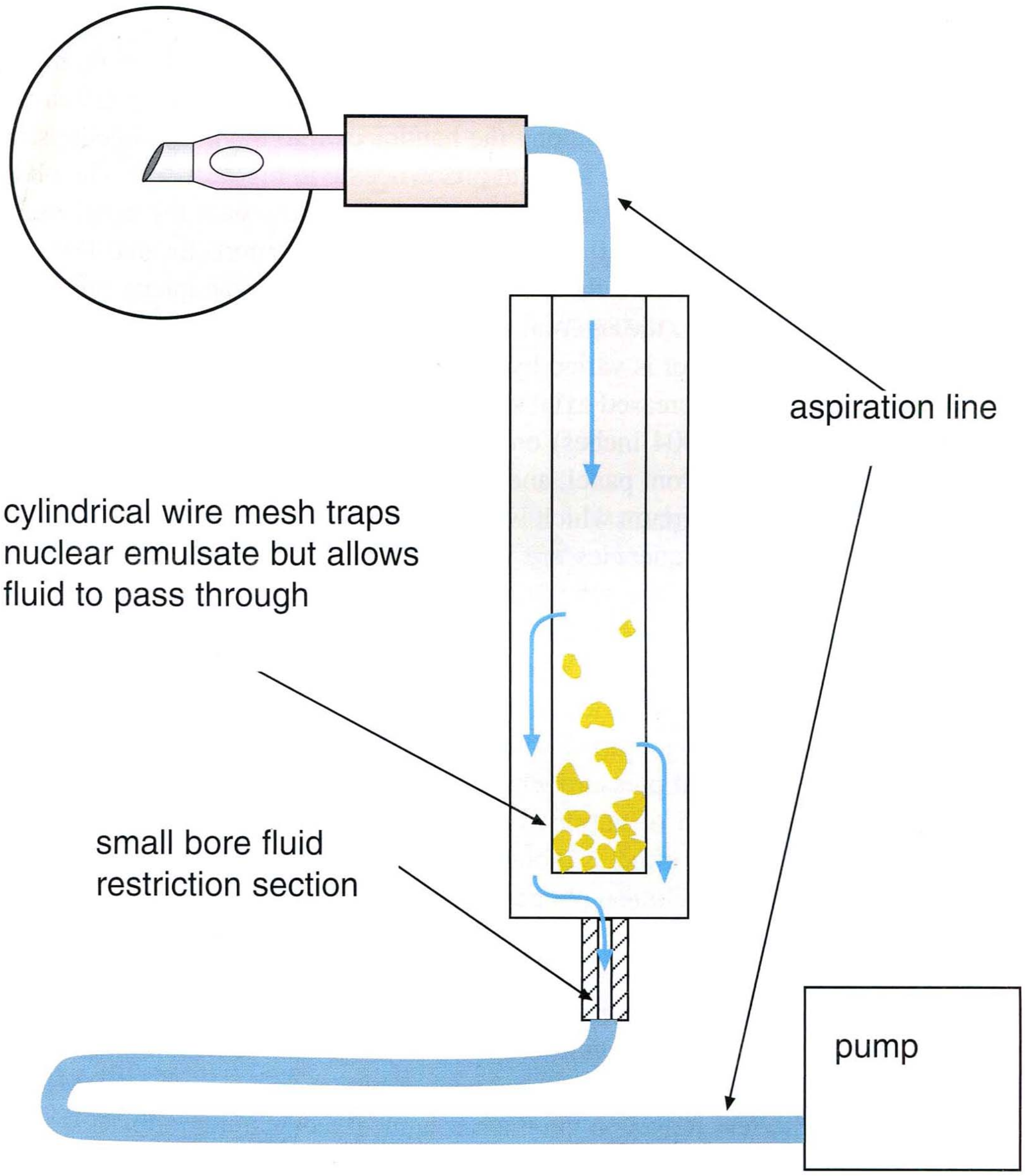

occlusion break
30" H_2O
vacuum limit 100 mm Hg
vacuum limit 160 mm Hg
vacuum limit 250 mm Hg
IOP
surge
anterior chamber collapse with IOP less than zero
0" H_2O
time

FIGURE 1-48-3

External Surge Suppression

As discussed previously, surge may be limited by the use of small inner diameter aspiration line tubing that has correspondingly higher fluidic resistance. However, a potential liability of this design is clogging of the line with nuclear emulsate, a frustrating occurrence that can cause surgery to be interrupted while the aspiration line is cleared or replaced. Although this was a problem with early designs of this tubing type by AMO, current high vacuum tubing by Alcon and AMO seem to work well. An intriguing modification of this goal of external aspiration line surge suppression is the **Cruise Control** designed by Alex Urich and marketed by Staar Surgical (**Figure 1-48-4**, **not to scale**). This device connects directly to the aspiration luer of the phaco handpiece, where it receives anterior chamber fluid and nuclear emulsate, with the latter filtered by the screen mesh. The filtered clear fluid then proceeds through an IA-sized opening (about 0.3 mm diameter), which serves the function of fluidic resistance and surge control. The fluid then connects to the normal aspiration tubing. By filtering the nuclear emulsate, this device achieves the goal of small diameter, high fluidic resistance, surge control essentially without the possibility of aspiration line clogging. This goal may also be substantially achieved with small bore phaco needles, which by definition emulsify the nucleus sufficiently to fit through the aspiration port so that clogging at this point would be unlikely, especially during application of ultrasound energy.

The sophisticated anterior chamber pressure monitoring systems on many modern phaco machines certainly help to maintain anterior chamber stability (see discussion of eye model in Figure 1-48-2); however, these mechanisms all have limitations in responsiveness due to inherent electromechanical delays. Conversely, fluidic resistance designs (eg, Cruise Control, MicroFlow/Flare Tip needle, smaller lumen aspiration tubing), along with low system compliance and tubing, provide virtually instantaneous surge modulation and are therefore desirable on many high vacuum phaco techniques.



aspiration line
cylindrical wire mesh traps nuclear emulsate but allows fluid to pass through
small bore fluid restriction section
pump

FIGURE 1-48-4

Ultrasound Overview

Besides setting fluidic parameters, the surgeon must also decide on the application of ultrasound power, which is produced most often by a piezoelectric crystal oscillating between approximately 25,000 and 60,000 times a second (Hz) for most machines. By definition, ultrasonic **frequency** is greater than 20,000 Hz; this frequency is fixed on a given ultrasonic handpiece. This energy is then transmitted and amplified along the handpiece into the phaco needle such that the primary oscillation is axial (green arrow at distal phaco needle in Figure 1-49). The phaco needle, which is manufactured in various bevel angles as shown, is hollow with the distal opening functioning as the aspiration port. Irrigating fluid flows out through two ports located 180° apart on the silicone sleeve. The blue silicone hub threads the sleeve onto the handpiece outer casing. The phaco needle threads directly into the internal mechanism of the handpiece containing the ultrasound generator. Ultrasound power is varied by changing the excitation voltage of the handpiece; increased voltage translates to increased axial **stroke length** at the phaco needle tip, up to a maximum of about 100 microns (0.004 inches) on most machines. Usually, a maximum ultrasound limit is preset on the machine's front panel, and the surgeon then titrates with linear pedal control the percentage of this preset maximum which is appropriate to a given intraoperative instant. Note that by definition, ultrasonic frequencies are inaudible; the buzzing sound often mistaken for "ultrasound" is actually caused by the sub-harmonic tones of the handpiece and tip.

The actual mechanism of action of ultrasonic phacoemulsification is somewhat controversial. One school of thought centers around the acoustic breakdown of lenticular material as a result of sonic wave propagation through the fluid medium. Another theory concerns the microcavitation bubbles produced at the distal phaco tip (Figure 1-62); the implosion of these bubbles produces brief instances of intense heat and pressure which are thought to emulsify adjacent lens material. Yet another potential mechanism of action is via the tip's axial oscillations through its stroke length; this resultant jackhammer effect is thought to mechanically break down lens material. This last mechanism also explains the clinical phenomenon of increasing repulsion of free-floating lens material with increasing ultrasound power levels; these levels need appropriate fluidic titration of the attractive parameters of flow and vacuum to counteract this repulsion (see Figure 2-5). Different ultrasonic handpiece frequencies are thought to facilitate different mechanisms of action. A lower frequency (ie, 28 kHz) is thought to better facilitate microcavitation bubble formation; furthermore, it is less likely to generate frictional heat. A higher frequency (ie, 40 kHz) is thought to cut more smoothly with less repulsion via the mechanical jackhammer effect.

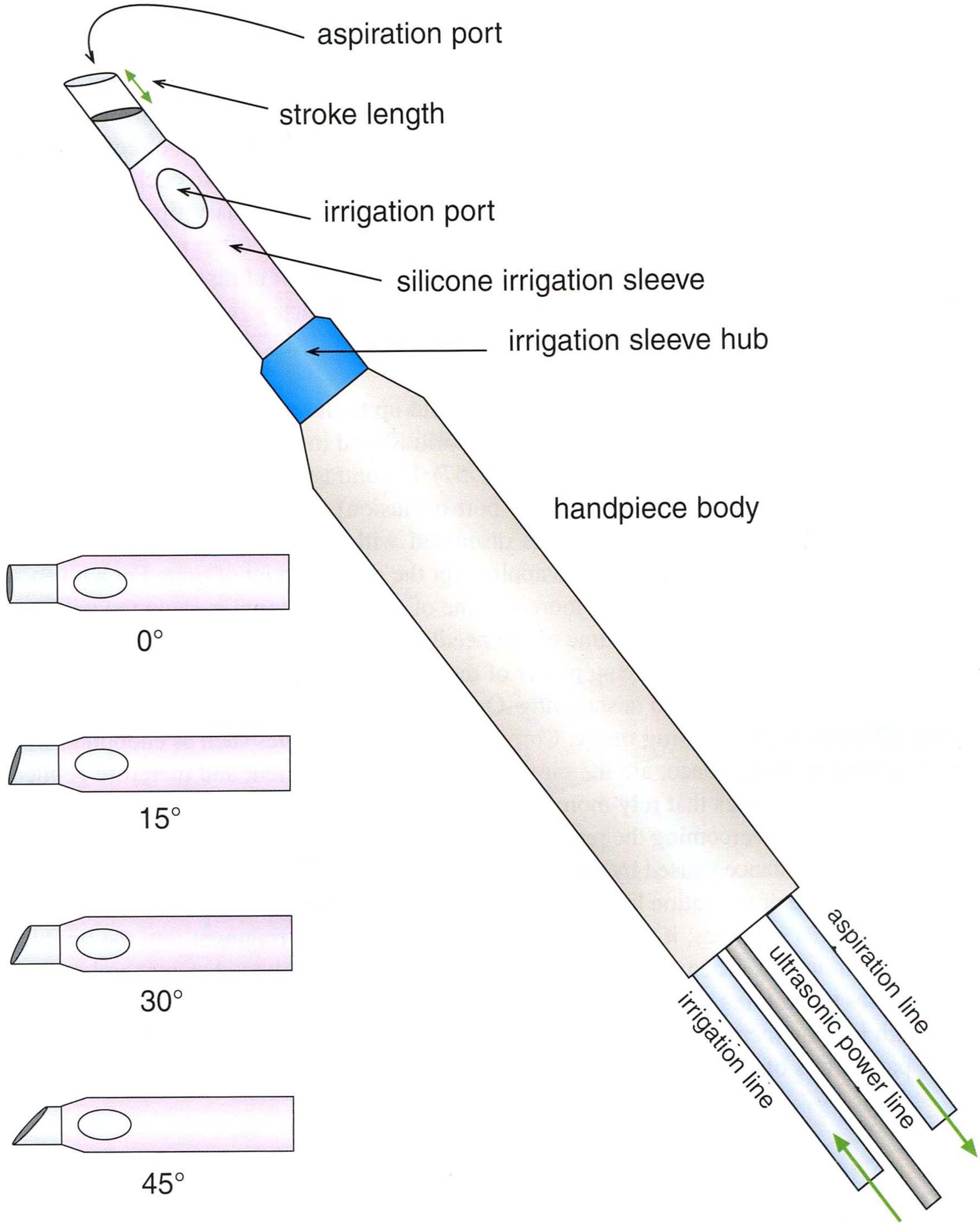

aspiration port
stroke length
irrigation port
silicone irrigation sleeve
irrigation sleeve hub
handpiece body
aspiration line
ultrasonic power line
irrigation line
0°
15°
30°
45°

FIGURE 1-49

Sculpt vs Occlude

By definition, sculpting involves removal of nuclear material by linear excursions of the phaco tip (straight blue arrow) with the aspiration port less than fully occluded (typically one third to one half occluded). The vibrating ultrasonic needle can effectively chisel away at the nucleus because it (the nucleus) is held in place by the zonules and capsule. It can be seen in Figure 1-50 why sculpting is a less efficient method of phacoemulsification relative to occlusion methods (ie, carouseling fragments into the tip), which typically involve a stationary tip into which nuclear material is fed (curved blue arrow) by vacuum. Occlusion mode is often used with quadrants or chopped fragments, and vacuum counteracts the repulsive action of ultrasound and grips these lens fragments to allow effective transmission of ultrasound energy into lenticular breakdown. Occlusion mode can also be used with entire nuclei, such as with Chip and Flip, Phaco Flip, and Tilt and Tumble methods.

With full occlusion of the tip, vacuum can build up to the maximum preset level; the deformational force provided by the vacuum augments ultrasound in aspirating the occluding fragment into the tip and out of the eye (see also Figure 1-57). In contrast, sculpting cannot efficiently build vacuum (due to lack of complete aspiration port occlusion) and therefore relies solely on ultrasonic breakdown of lenticular material as discussed with Figure 1-49. In both illustrations in Figure 1-50, the same ultrasound level is applied for the same amount of time. For a given amount of ultrasound power per unit of time, more volume of nuclear material is aspirated with an occlusion method because the entire volume of the needle (as defined by its inner diameter) is utilized as vacuum augments the emulsifying power of the applied ultrasound, as opposed to the fractional volume of the needle utilized in sculpting. **Occlusion mode phaco is therefore more time and energy efficient than sculpting mode**. Correspondingly, techniques such as chopping, which use mostly occlusion mode phaco, are the most time and energy efficient and therefore gentler to the eye relative to techniques that rely more on sculpting.

In addition to overcoming the repulsive action of the ultrasonic needle, vacuum also helps to overcome any resistance caused by possibly large aspirated nuclear fragments so that they do not clog the handpiece or aspiration line. Flow functions to drive along nuclear material that was emulsified into smaller particles; it also continues to feed the nuclear fragment into the tip during the intermittent moments when ultrasound breaks down the material so that incomplete occlusion compromises the holding efficiency of vacuum. The combination of attracting fragments to the tip along with feeding them into the tip against the repulsive action of ultrasound using the combined fluidic parameters of vacuum and flow is known as **followability**.

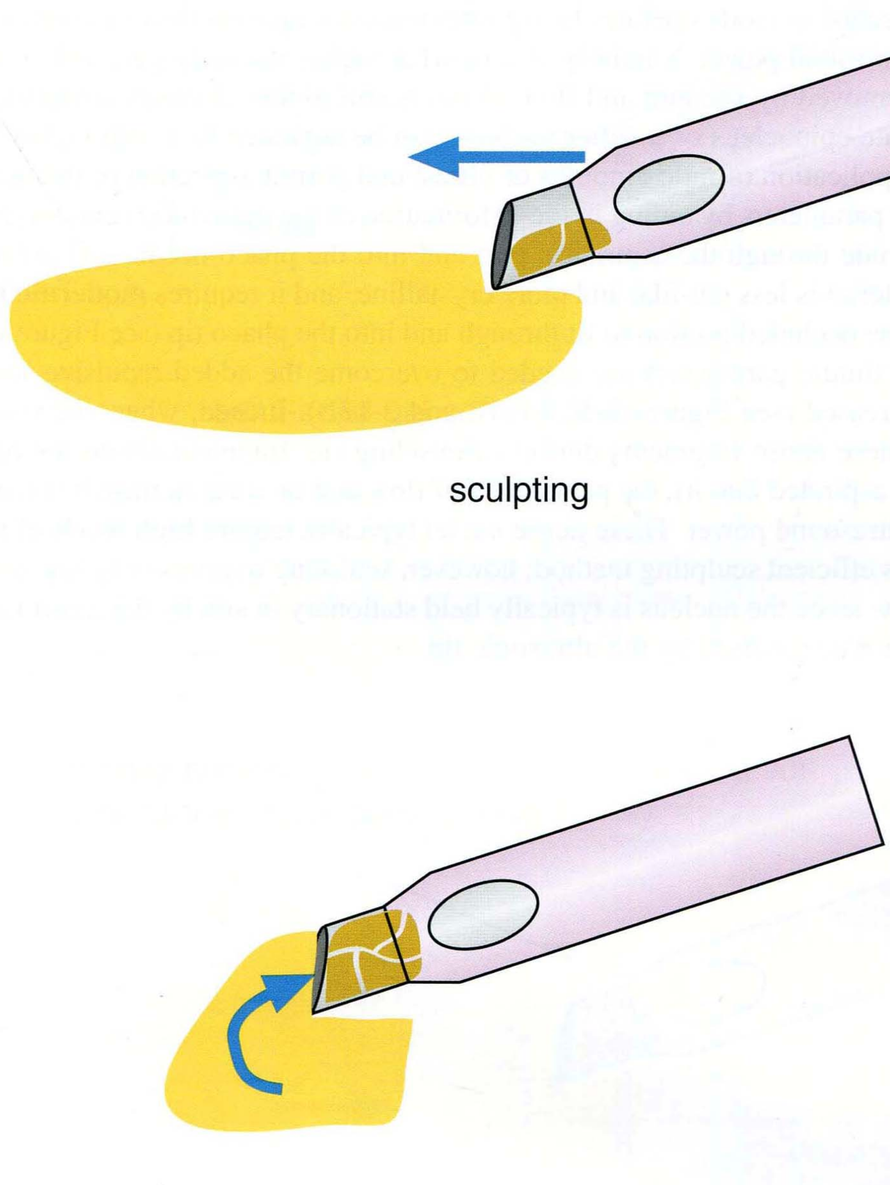
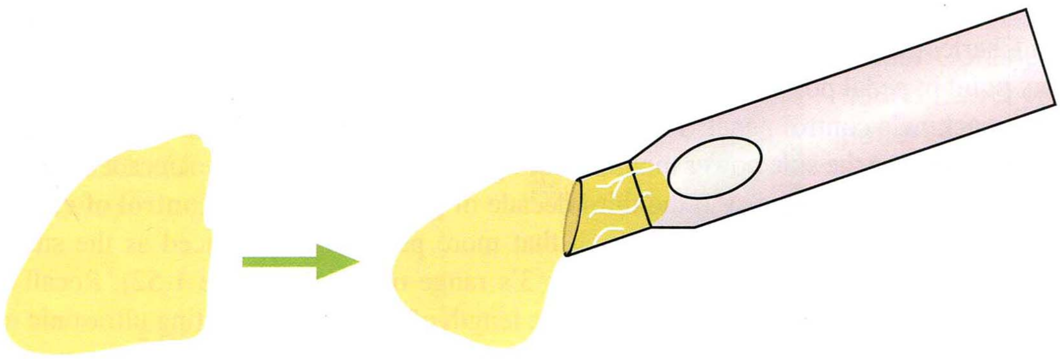


FIGURE 1-50

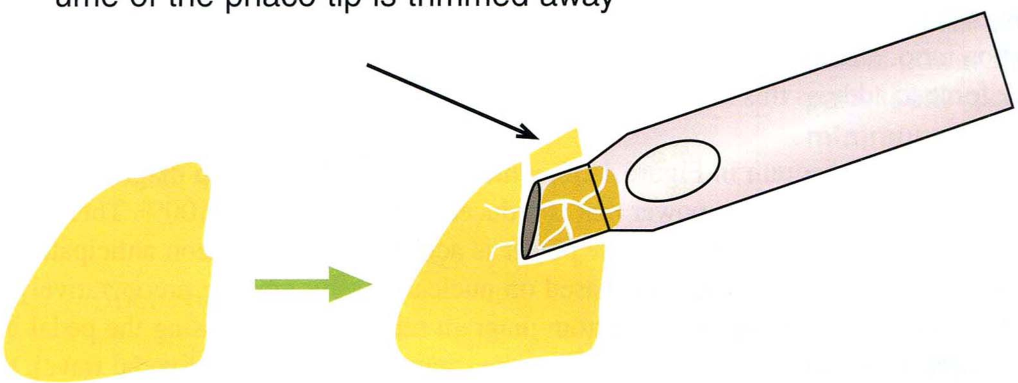
Ultrasound: Gel vs Solid

At one extreme, occlusion mode operates to aspirate (remove) aqueous (low viscosity) without the need for any ultrasound power. Similarly, a somewhat higher viscosity gel, such as a viscoelastic, can also be removed by vacuum and flow alone. A still higher viscosity material, such as the semi-solid gel state epinucleus or a softer nucleus, can be aspirated by a still higher vacuum/flow, although the application of mild amounts of ultrasound permit aspiration of the material with lower, safer fluidic parameters by aiding in the deformation of the material (Figures 1-51 and 2-13) so that it can extrude through the aspiration port and into the phaco needle and aspiration line. Denser nuclear material is less gel-like and more crystalline, and it requires **moderate ultrasound** in order to trim the occluded portion to fit through and into the phaco tip (see Figure 1-51); correspondingly higher fluidic parameters are needed to overcome the added repulsive force as ultrasound power is increased (see Figures 2-5, 2-13A, and 2-13B). Indeed, when encountering **poor followability** of these dense fragments during carouseling (ie, fragment chattering against the tip rather than being aspirated into it), the parameters of flow and/or vacuum must be increased rather than increasing ultrasound power. These dense nuclei typically require **high levels of ultrasound** when using a less efficient sculpting method; however, sculpting requires only low vacuum and low to moderate flow since the nucleus is typically held stationary in situ by the intact nuclear body and therefore cannot be repulsed by the ultrasonic tip.



semi-solid gel soft nucleus

excess nuclear material beyond the internal volume of the phaco tip is trimmed away



hard crystalline nucleus

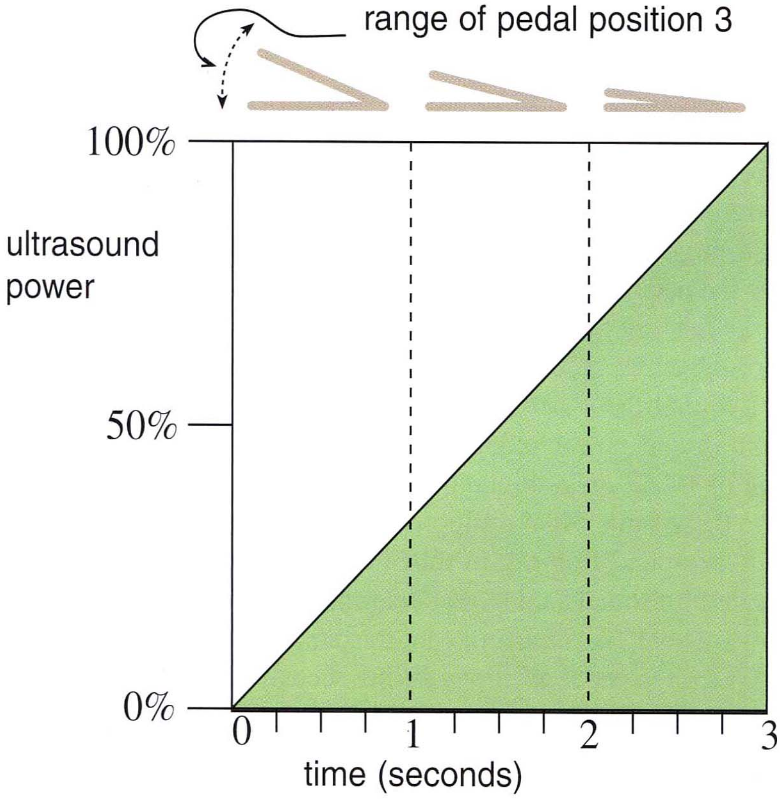
FIGURE 1-51

Ultrasound Power Modulations: Linear Continuous

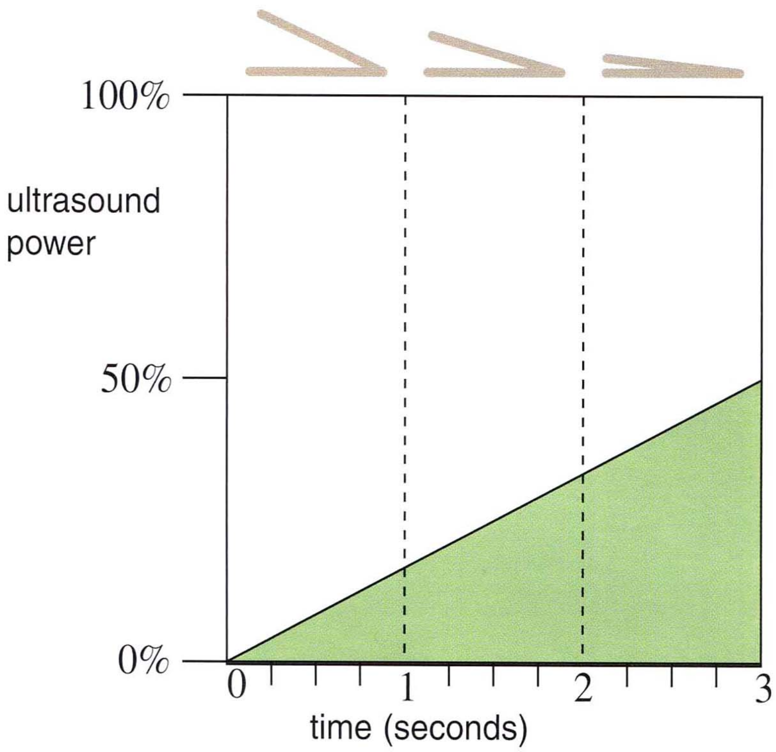
When Charles Kelman, MD developed the first phaco machine over 30 years ago, the ultrasound at any point in pedal position 3 was either "on" or "off" continuously at a level that had been preset on the machine's control panel. This **Fixed Panel Control** of **continuous ultrasound** (see Figure 1-53) persisted as the sole power modality for approximately the first two decades of phaco. The first major advance, introduced in the third decade of phaco, was **linear control of continuous ultrasound power** within position 3, such that more power was produced as the surgeon depressed the pedal progressively within position 3's range of travel (Figure 1-52). Recall that increased phaco power translates to increased stroke length of the axially vibrating ultrasonic needle (Figure 1-49), which in turn produces not only more emulsifying potential but also more repulsive force that requires greater fluidic compensation (higher vacuum and/or flow settings) especially when using occlusion mode techniques. However, the predominant technique when Linear Pedal control was introduced involved primarily sculpting, and because sculpting depended primarily on phaco power, the new control modality was very helpful (see Figures 2-9 and 2-10).

The upper diagram in Figure 1-52 depicts a pedal being **progressively** depressed through position 3's range of travel starting at time 0 and ending at the bottom of pedal travel after an elapsed time of 3 seconds; **note the schematic foot pedals seen in side view at the top of each diagram**. The **minimum phaco power** (that which is obtained at the top of position 3's travel) is set to 0%, while the **maximum phaco power** (obtained at the bottom of position 3's travel) is set to 100%. Note the linear rise in phaco power (green area) that corresponds to the progressive depression of the pedal. Realize that 100% phaco power is somewhat arbitrary, as **no standardization currently exists in the industry regarding phaco power**; each machine produces a different power at the 100% level, with variances due to applied excitation voltage, ultrasonic horn amplification ratio, efficiency of the piezoelectric crystal driver, etc. Howard Fine, MD has organized a task force to address this industry shortcoming in the hope of achieving an ultrasonic power standard.

Note the bottom diagram in Figure 1-52, which is identical to the top diagram with the one exception of the maximum phaco power that is reduced to 50% instead of 100%. Therefore, at the bottom of position 3's range of travel, 50% power is achieved. If the surgeon anticipates a maximum need for ultrasound power of 50% based on nuclear density grading preoperatively, then it is advantageous to use the setup of the bottom diagram rather than depressing the pedal halfway in the top diagram. Because both diagrams have the same physical range of pedal travel, the bottom diagram provides better **control sensitivity** for the anticipated range of 0 to 50%.



Linear Continuous ultrasound power machine panel settings:
minimum 0%
maximum 100%
Foot pedal is **progressively depressed** from top of position 3 to the bottom of position 3 over a 3 second time interval, illustrating the correspondingly continuous rise in ultrasound power (green) over that time period.



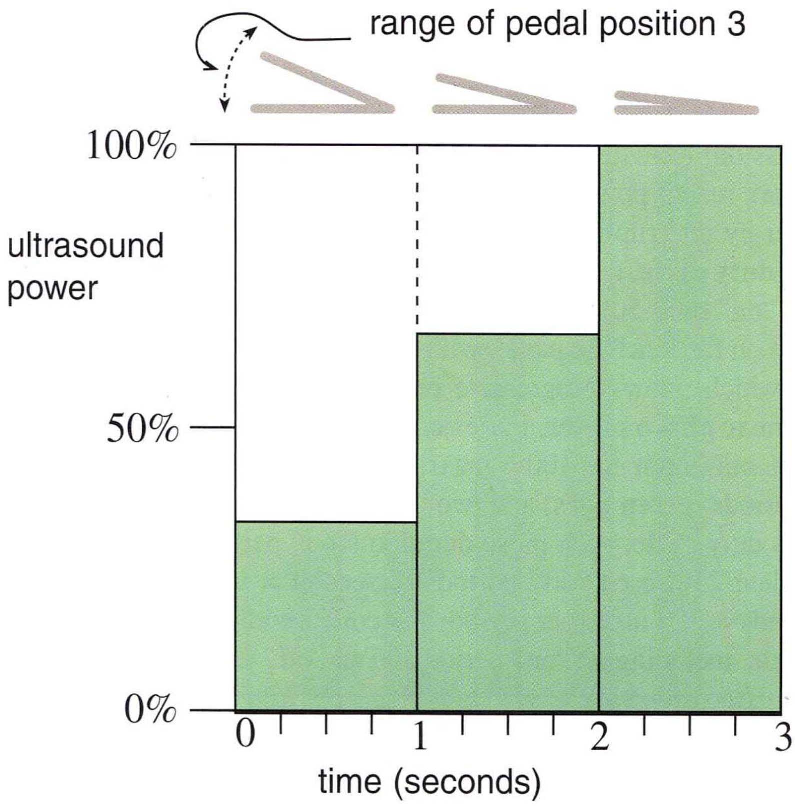
Linear Continuous ultrasound power machine panel settings:
minimum 0%
maximum 50%
Foot pedal is **progressively depressed** from top of position 3 to the bottom of position 3 over a 3 second time interval, illustrating the correspondingly continuous rise in ultrasound power (green) over that time period.

FIGURE 1-52

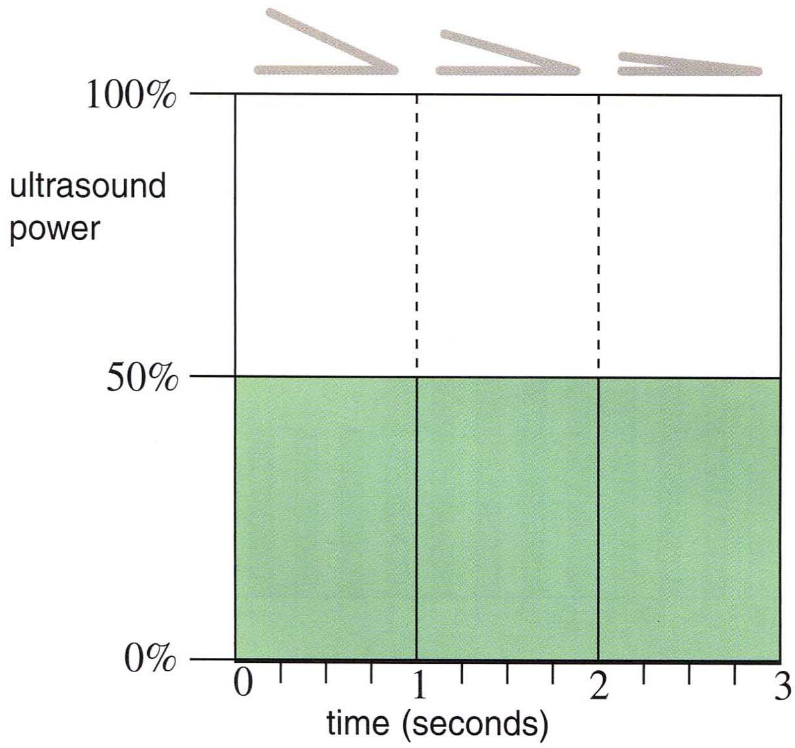
Ultrasound Power Modulations: Fixed Panel Continuous

By comparison with Linear Control of continuous ultrasound, Fixed Panel Control of continuous ultrasound is considerably more limiting with regard to surgical flexibility. To illustrate this, Linear Control is represented in the upper diagram of Figure 1-53 differently than Figure 1-52, in that the latter had the pedal progressively depressed through position 3's range, whereas both diagrams in Figure 1-53 have the pedal **sequentially** placed at three distinct positions within range 3's travel. During the first second, the pedal is one third depressed within range 3's travel, while it is two thirds depressed for the entire second second. The pedal is fully depressed during the third second on the graph. Note that these pedal positions on this particular linear control machine correspondingly yield ultrasound power levels of 30%, 70%, and 100%, respectively, assuming a maximum preset value of 100% and a minimum preset of 0%.

Note the different response to these same pedal positions in the bottom diagram of Figure 1-53, which illustrates Fixed Panel Ultrasound Control. In this modality, there is no maximum or minimum setting, but rather a single ultrasound setting that determines the power delivered anywhere in position 3's range of travel. Therefore, with a fixed ultrasound setting of 50%, this same power level is obtained at each of the three pedal positions during seconds 1, 2, and 3. If the surgeon has insufficient power (eg, phaco needle pushing rather than carving through the nucleus during sculpting), then he or she must pause and request that the scrub technician or circulating nurse raise the power on the machine's panel control. If that new power is too high, a new pause and request are required. In contrast to this awkward surgical control modality, a surgeon using linear control of ultrasound power needs only to move the pedal appropriately within position 3 to modulate ultrasound power.



Linear Continuous ultrasound power machine panel settings:
minimum 0%
maximum 100%
Foot pedal is **sequentially depressed** to three positions within position 3:
1st second: 1/3 depressed
2nd second: 2/3 depressed
3rd second: fully depressed



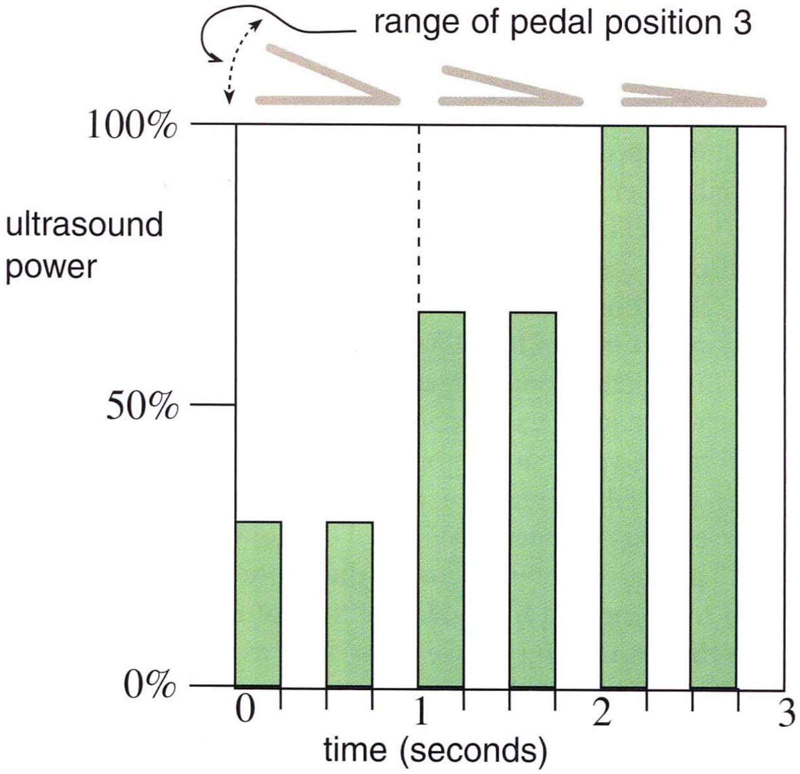
Fixed Continuous ultrasound power machine panel settings:
50%
Foot pedal is **sequentially depressed** to three positions within position 3:
1st second: 1/3 depressed
2nd second: 2/3 depressed
3rd second: fully depressed

FIGURE 1-53

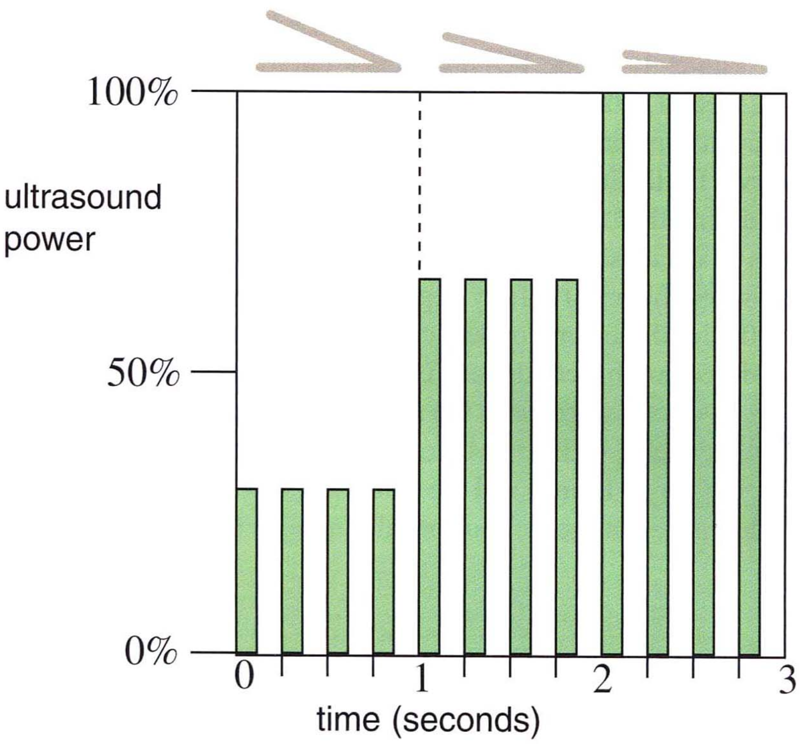
Ultrasound Power Modulation: Pulse Mode

Whereas the foregoing discussions have dealt with continuous ultrasound being present within position 3's range of travel, more recent power modulations, including Pulse Mode and Burst Mode, modulate ultrasound power by interrupting it with periods of inactivity within position 3. **Pulse Mode** typically has a **50% duty cycle**, meaning that for a given time interval with position 3 engaged, the phaco power was "on" only 50%, or half of the time. The surgeon sets a number of **fixed Pulses Per Second (PPS)** on the machine panel, with a typical range being one to fifteen. The PPS setting remains fixed, which allows progressive pedal movement within position 3's range of travel to still modulate **linear phaco power**. For example, the upper diagram in Figure 1-54 has linear power settings of 0% minimum and 100% maximum along with a pulse setting of 2 PPS. Two PPS means two "on" periods (**green bars**) and two "off" periods (total of 2 duty cycles) for each second, and given a 50% duty cycle, each pulse duration ("on" period) will be 250 milliseconds alternating with equivalent 250 msec "off" periods (1 second = 1000 milliseconds, or msec; 1 second divided by 4 periods = 250 msec per period; 1 second divided by 2 duty cycles = 500 msec per each whole duty cycle, including an "on" period and an "off" period). **Note that the marks on the x-axis denote 250 msec intervals**.

Note how linear power control is present in both graphs, with lower pedal positions within pedal range 3 producing correspondingly higher power levels (taller green bars). However, the duration of the pulse periods remains constant within each graph. The lower graph in Figure 1-54 increases the pulse setting to 4 PPS. Using the same derivation as in the preceding paragraph, 4 PPS translates to 4 "on" and 4 "off" periods in each second for a total of 4 duty cycles (8 equivalent time periods, assuming a 50% duty cycle). Therefore, each pulse duration in the lower graph will be 125 msec, as will be each "off" period as well (1 second divided by 8 time periods = 125 msec per period).



Pulse Mode
Linear ultrasound power
machine panel settings:
power:
minimum: 0%
maximum: 100%
Pulses per second (pps):
2 pps
duty cycle: 50%
Foot pedal is **sequentially depressed** to three positions within position 3:
1st second: 1/3 depressed
2nd second: 2/3 depressed
3rd second: fully depressed



Pulse Mode
Linear ultrasound power
machine panel settings:
power:
minimum: 0%
maximum: 100%
Pulses per second (pps):
4 pps
duty cycle: 50%
Foot pedal is **sequentially depressed** to three positions within position 3:
1st second: 1/3 depressed
2nd second: 2/3 depressed
3rd second: fully depressed

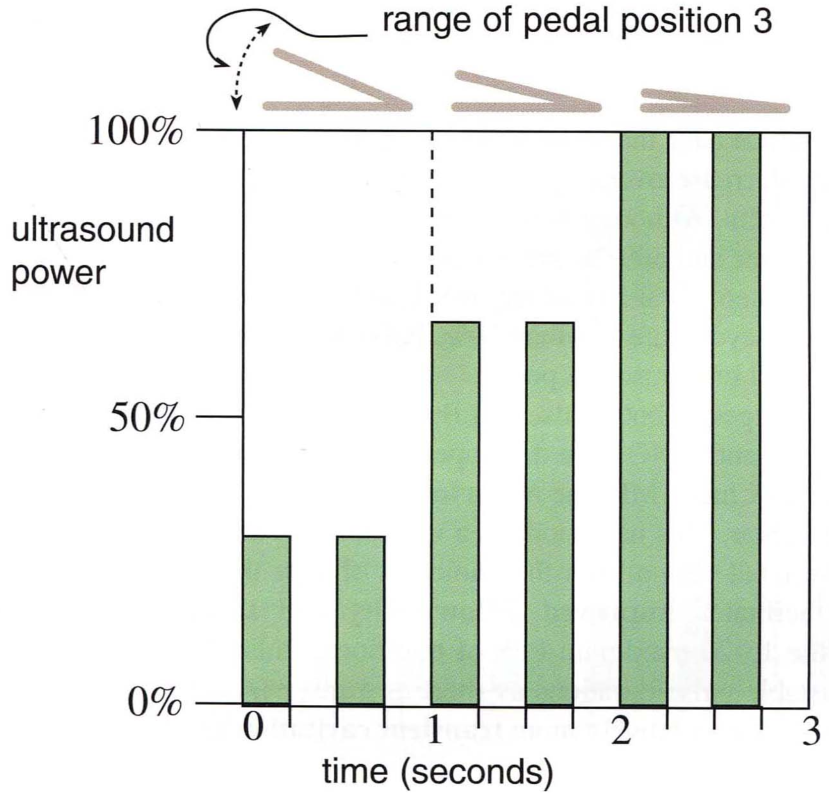
FIGURE 1-54

Ultrasound Power Modulation: Burst Mode

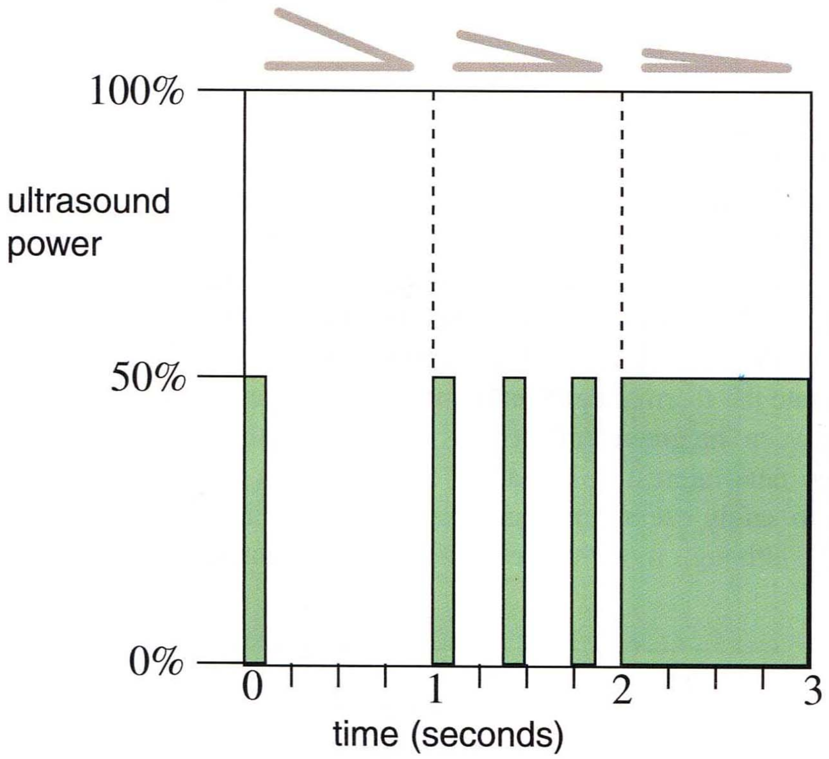
In contrast to Pulse Mode, which uses pedal movement within range 3's travel to modulate phaco power with a fixed number of pulses per second, **Burst Mode** uses the pedal movement to modulate the interval between bursts (ie, **linear control of number of bursts per second**) while **phaco power remains fixed** at the machine panel setting. The surgeon can also often choose a **burst duration** (the range on the Bausch & Lomb Millennium is from 4 to 600 msec). A typical time interval at the beginning of position 3's range of travel would be 2.5 seconds between bursts (eg, Alcon Legacy and Infiniti, AMO Sovereign); some surgeons have advocated this setting for initially impaling the nucleus with such techniques as chopping (eg, Howard Fine's Choo Choo Chop and Flip Method). The rest interval between bursts progressively decreases as the pedal is depressed further into position 3. When the pedal is placed at a position two thirds down in range 3, this particular machine produces three bursts per second (Figure 1-55, lower diagram). **To reiterate proper terminology, the "on" period is referred to as the pulse or burst duration, whereas the "off" period is referred to as the rest interval. The total of an "on" period plus an adjacent "off" period is the cycle time, and a duty cycle (expressed as a percentage) is the proportion of the "on" period relative to the cycle time.**

Note that unlike Pulse Mode with its nominal 50% duty cycle (see upper diagram in Figure 1-55), **burst mode allows duty cycles that are shorter than 50%** (ie, the "off" cycle is longer than the "on" cycle). For example, with the pedal depressed one third into position 3 during the first second on the bottom graph of Figure 1-55, the 125 msec burst duration represents a 12.5% duty cycle; 125 msec divided by 1 second (1000 msec) total cycle time = 12.5%. Shorter duty cycles may be beneficial with regard to preventing incisional burns by allowing more **thermal relaxation time** during the rest interval for the incisional protein to dissipate the heat that was produced by ultrasonic needle friction during the "on" period.

As the burst interval continues to decrease with continued pedal depression, the duty cycle reaches and surpasses 50%. Indeed, when the pedal is fully depressed, the rest interval has become zero, the duty cycle has become 100%, and the surgeon has continuous phaco power (during the third second on the bottom graph). Moreover, this continuous phaco power is at a fixed panel level, just like the phaco machines from three decades ago, with the attendant limitations discussed with Figure 1-53. Therefore, most of the advantage of Burst Mode occurs when the duty cycle is less than 50%. Recent machines such as the Alcon Infiniti and the Bausch & Lomb Millennium allow the surgeon to limit the maximum duty cycle at the limit of pedal range 3's travel (ie, so that it is less than 50%).



Pulse Mode
Linear ultrasound power
machine panel settings:
power:
minimum: 0%
maximum: 100%
Pulses per second (pps):
2 pps
Foot pedal is **sequentially depressed** to three positions within position 3:
1st second: 1/3 depressed
2nd second: 2/3 depressed
3rd second: fully depressed



Burst Mode
Fixed ultrasound power
machine panel settings:
power:
50%

Burst duration: 125 msec

Foot pedal is **sequentially depressed** to three positions within position 3:
1st second: 1/3 depressed
2nd second: 2/3 depressed
3rd second: fully depressed

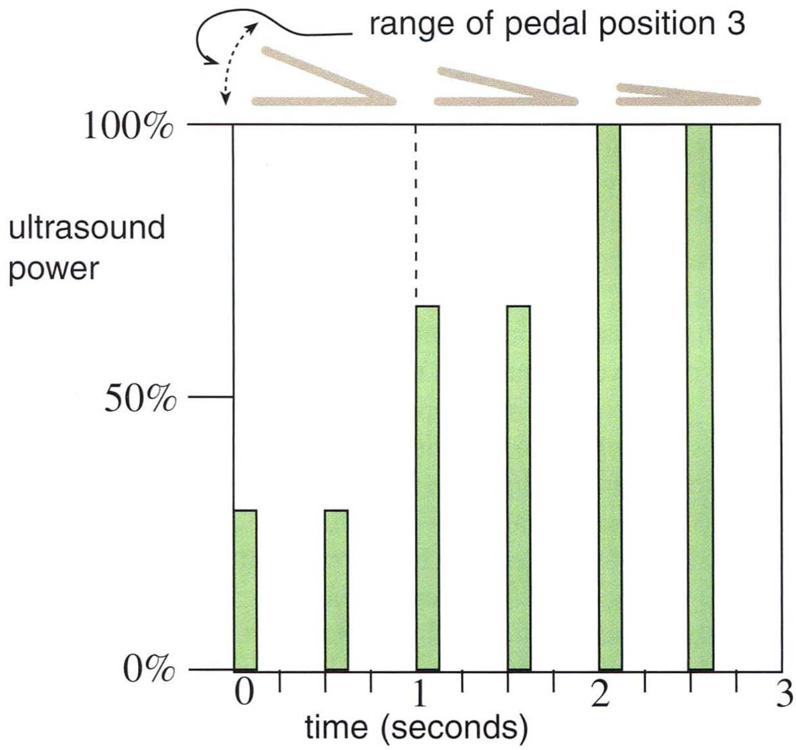
FIGURE 1-55

Ultrasound Power Modulation: HyperPulse

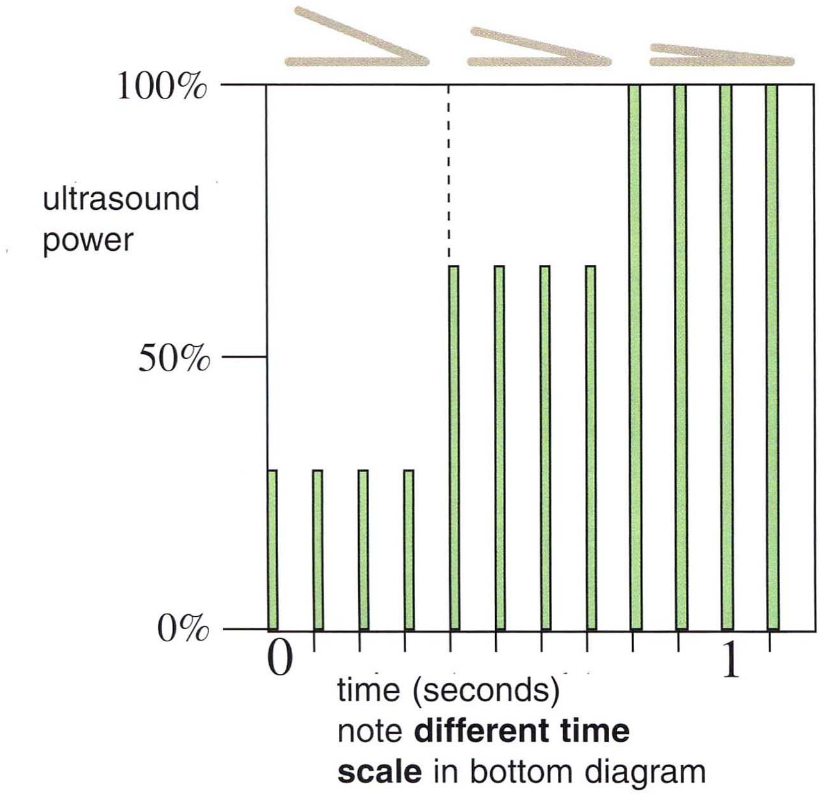
Both Pulse Mode and Burst Mode have the advantage over continuous power modes of "off" cycles that improve followability, decrease overall phaco time (see Figure 1-57), and allow for thermal relaxation of incisional protein. Although Burst Mode has some disadvantages such as fixed nonlinear control of phaco power and 50% or greater duty cycles in roughly the last half of position 3's travel, it does have the theoretical advantage over Pulse Mode of better thermal protection for the incision when the duty cycles are less than 50%. Pulse Mode has the advantage over Burst Mode in allowing linear control of ultrasound power.

In order to combine the advantages of both Pulse and Burst Modes while limiting their disadvantages, Alcon, Bausch & Lomb, and AMO have developed a modified Pulse Mode known as HyperPulse, a name coined by David Chang, MD; the Alcon Infiniti also calls it HyperPulse, while the AMO Sovereign terms it WhiteStar. This new mode is a variation of Pulse Mode that retains linear control of ultrasound power but also allows the choice of shorter duty cycles to enable longer "off" periods, which facilitates **improved followability** and **thermal protection**. Furthermore, in comparison to the 15-20 maximum PPS of traditional Pulse Mode, HyperPulse allows up to 100 PPS with adjustable pulse durations as short as 5 msec (Alcon Infiniti). These rapid short pulses are thought to produce relatively more **transient cavitation** that increases ultrasonic efficiency of emulsification (see Figure 1-62).

The upper diagram in Figure 1-56 illustrates HyperPulse Mode with settings of 2 PPS, 25% duty cycle, and linear control of ultrasound power. Recalling that each mark on the x-axis represents 250 msec intervals, one can see that in the first half second (500 msec), ultrasound is on for only 125 msec, or 25% of the time, while the rest interval is 375 msec. Compare this to the top diagram in Figure 1-54, in which both the "on" period and the "off" period are each 250 msec. In all probability, both 250 msec and 375 msec off times in this comparison are more than adequate for thermal relaxation. The real benefit of shorter duty cycles will likely be found in more rapid pulse rates, such as that illustrated in the bottom diagram of Figure 1-56, in which the time scale has been reset on the x-axis, with each mark now representing 100 msec intervals instead of the 250 msec intervals in the preceding diagrams. Even with a magnified view of this more rapid pulse setting (10 PPS), one can appreciate the thermal benefits stemming from the predominance of the rest intervals (white space) in between the green "on" periods representing the 25% duty cycle. In fact, this new mode has fostered new interest in Bimanual Microincision Phaco (a.k.a. microphaco) because of the potential to safely use a bare phaco needle without an insulating silicone irrigation sleeve (see Figure 1-2), although more studies are needed to consistently validate this premise.



Hyper-Pulse Mode
Linear ultrasound power
machine panel settings:
power:
minimum: 0%
maximum: 100%
Pulses per second (pps):
2 pps
duty cycle: 25%
Foot pedal is **sequentially depressed** to three positions within position 3:
1st second: 1/3 depressed
2nd second: 2/3 depressed
3rd second: fully depressed



Hyper-Pulse Mode
Linear ultrasound power
machine panel settings:
power:
minimum: 0%
maximum: 100%
Pulses per second (pps):
10 pps
duty cycle: 25%
Foot pedal is **sequentially depressed** to three positions within position 3:
1st second: 1/3 depressed
2nd second: 2/3 depressed
3rd second: fully depressed

FIGURE 1-56

Ultrasound Power Modulations: Decreased Ultrasound Time

In addition to incisional thermal protection, ultrasound power modulations have beneficial effects to followability because the "off" interval allows the occluding nuclear fragment to better re-engage the aspiration port without the repulsive action of the "on" cycle of ultrasound. Moreover, this mechanism of action actually serves to decrease overall ultrasound time for a given case, as has been validated by studies from Drs. Howard Fine, Mark Packer, and Richard Hoffman. Prior to these studies, it was assumed that no aspiration of lens material occurred during the "off" cycle, and that Pulse Mode with a 50% duty cycle would use the same amount of total ultrasound time but take twice as long overall for a given cataract as compared to continuous phaco power (ie, 100% duty cycle). Figure 1-57 proposes a mechanism of action that explains why the total ultrasound time is less with power modulation (Pulse or Burst) as shown by the Fine et al studies.

Figure 1-57-1: A nuclear fragment has been engaged by vacuum at the aspiration port (pedal position 2). The effect of vacuum is illustrated by the red area in the fragment (spreading from area "1" to area "2"), where the pressure differential is causing **stress** (see Figure 5-1) on the crystalline structure of the lens material but is insufficient for this particular density of cataract to break it down and aspirate it.

Figure 1-57-2: Ultrasonic Pulse Mode is engaged with pedal position 3. Note the axially vibrating phaco needle (double-ended blue arrow) during this initial "on" period of Pulse Mode, which has broken down some of the occluding material within the aspiration port around area 1 or the nuclear fragment, allowing its aspiration (see green arrow). Moreover, the ultrasonic vibration has produced stress fractures within the crystalline structure of the cataract (white lines extending into area 2 of the fragment), thereby weakening it.

Figure 1-57-3: At the beginning of the next "off" period, the initially broken down lens material is drawn further into the phaco needle. Additionally, the same vacuum that was insufficient to aspirate the intact lens material is now able to draw more material in that was weakened by the ultrasonic stress fractures induced above (straight green arrow). The previous "on" pulse and subsequent aspiration of material disrupted the vacuum seal at the aspiration port, resulting in less stress on the nuclear fragment (decreased red area in Figure 1-57-3), but the fluidics now autoregulate (machine pump produces flow in addition to vacuum with imperfect vacuum seal) to cause the nuclear fragment to better rotate and reseal into the aspiration port (curved green arrow). Note that area 1 of the original fragment is now aspirated more deeply within the needle, and that area 2 is starting to be aspirated as it is drawn closer. Fluidics are able to more efficiently re-engage the fragment during this "off" period because of the absence of repulsive ultrasound.

Figure 1-57-4: The process described in Figure 1-57-3 has now resulted in the fragment being fully re-engaged. Note that the lens fragment is now smaller after breakdown and aspiration of part of its volume (ie, from point "1" to point "2"). Note also that the area of stress fractures has largely been aspirated and the vacuum is now again engaging intact nucleus and holding it firmly (see red area) in preparation for the next "on" period; this firm grip, made possible by the absence of the stress fractures and the degraded vacuum seal that was present in Figures 1-57-2 and 1-57-3, will facilitate much better ultrasonic efficiency during the next "on" period and contributes further to the time efficiency of Pulse and Burst Modes.

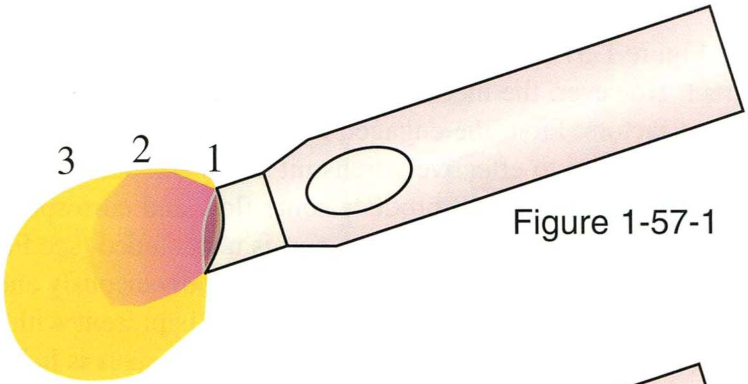


Figure 1-57-1

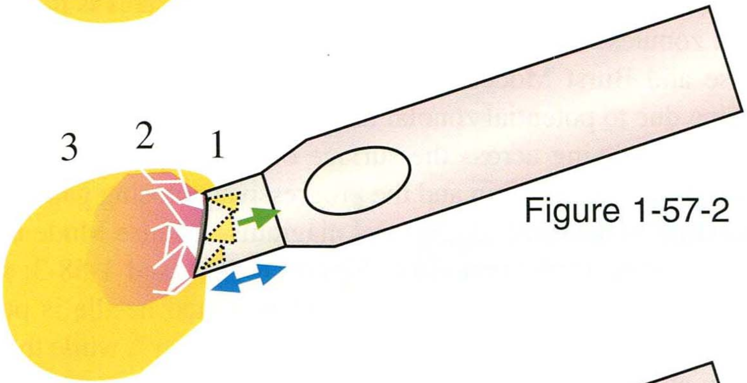


Figure 1-57-2

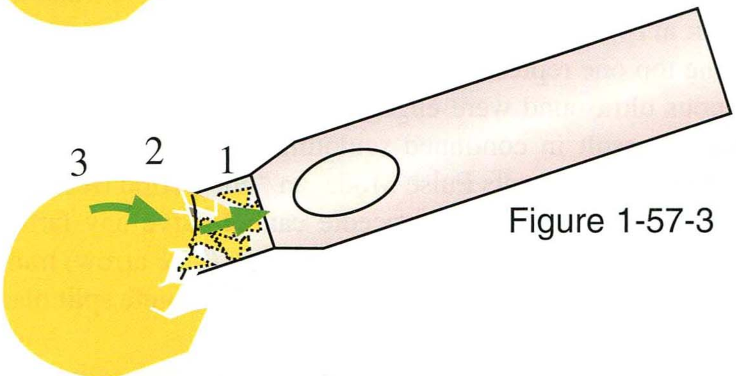


Figure 1-57-3

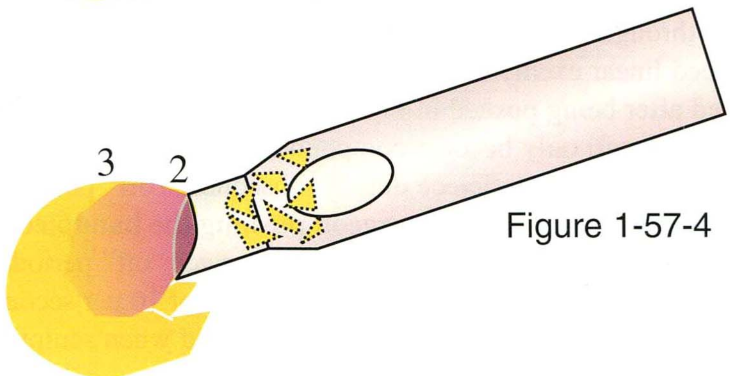


Figure 1-57-4

FIGURE 1-57

Pulse and Burst Modes Contraindication with Sculpting

As discussed with Figure 1-57, Pulse and Burst Modes result in decreased overall ultrasound times for a given cataract. However, the mechanism of action for this phenomenon as illustrated depends on two important factors. First, the engaged lens fragment must completely occlude the aspiration port in order for vacuum to effectively transmit stress and deformational force; incomplete occlusions such as with sculpting will produce some flow and correspondingly less deformation and aspiration to the extent that the aspiration port is unoccluded (see Figures 1-50 and 2-5). Second, the engaged lens fragment must be free-floating to spontaneously and repeatedly reengage as shown in Figures 1-57-3 and 1-57-4; this characteristic is present with lens quadrants or chopped fragments but is not present with sculpting because the nucleus is held stationary by the surrounding capsule and zonules.

Not only are Pulse and Burst Modes inefficient when sculpting, they are relatively contraindicated with sculpting due to potential zonular damage that could ensue with their use. Figure 1-58 depicts a phaco needle moving across the surface of the nucleus with a constant forward motion; note the **blue arrow** at the distal tip and the progressively closing gap between the tip and the **green dashed centerline** in the three progressive diagrams. A Pulse Mode is engaged whereby the phaco needle is vibrating ("on" period) in Figures 1-58-1 and 1-58-3; note the **double-headed green arrow** at the tip. As the ultrasonically active phaco needle is pushed forward in Figure 1-58-1, it carves through the nucleus from point "x" to point "y", while the nucleus remains stationary; note the **black arrows** that are vertically aligned, the bottom one representing the center of the nucleus and the top one representing the center reference for the entire diagram (green dashed line). If continuous ultrasound were engaged, then the continued linear excursion of the needle (blue arrow) would result in continued sculpting onward from point "y" to point "z". However, because this diagram represents Pulse Mode, an "off" period (rest interval) is present in Figure 1-58-2, and therefore the nonvibrating needle cannot carve any farther past point "y"; instead, the continued linear excursion of the phaco handpiece (blue arrow) translates into a pushing force (**red arrow**) that correspondingly displaces the nucleus (note split black arrows), stressing and possibly breaking zonules.

During the next "on" period (Figure 1-58-3), the ultrasonically active phaco needle (green arrow) can again carve through the nucleus, now proceeding from point "y" to point "z" corresponding to the continued linear excursion of the handpiece (blue arrow). However, note that the nucleus is still displaced after being pushed in Figure 1-58-2 (split black arrows), indicating continued zonular stress, which will only become compounded (black arrows splitting further apart) with further linear excursion of the handpiece during subsequent "off" periods. **This problem is exacerbated by rapid linear excursions (ie, surgeon pushing the handpiece across the nucleus quickly) and by low pulse or burst rates** which have longer "off" periods during which the nucleus is pushed and the zonules are stressed; pulse/burst rates of 10 per second or higher should approach the safety and efficacy profile of continuous ultrasound when sculpting.

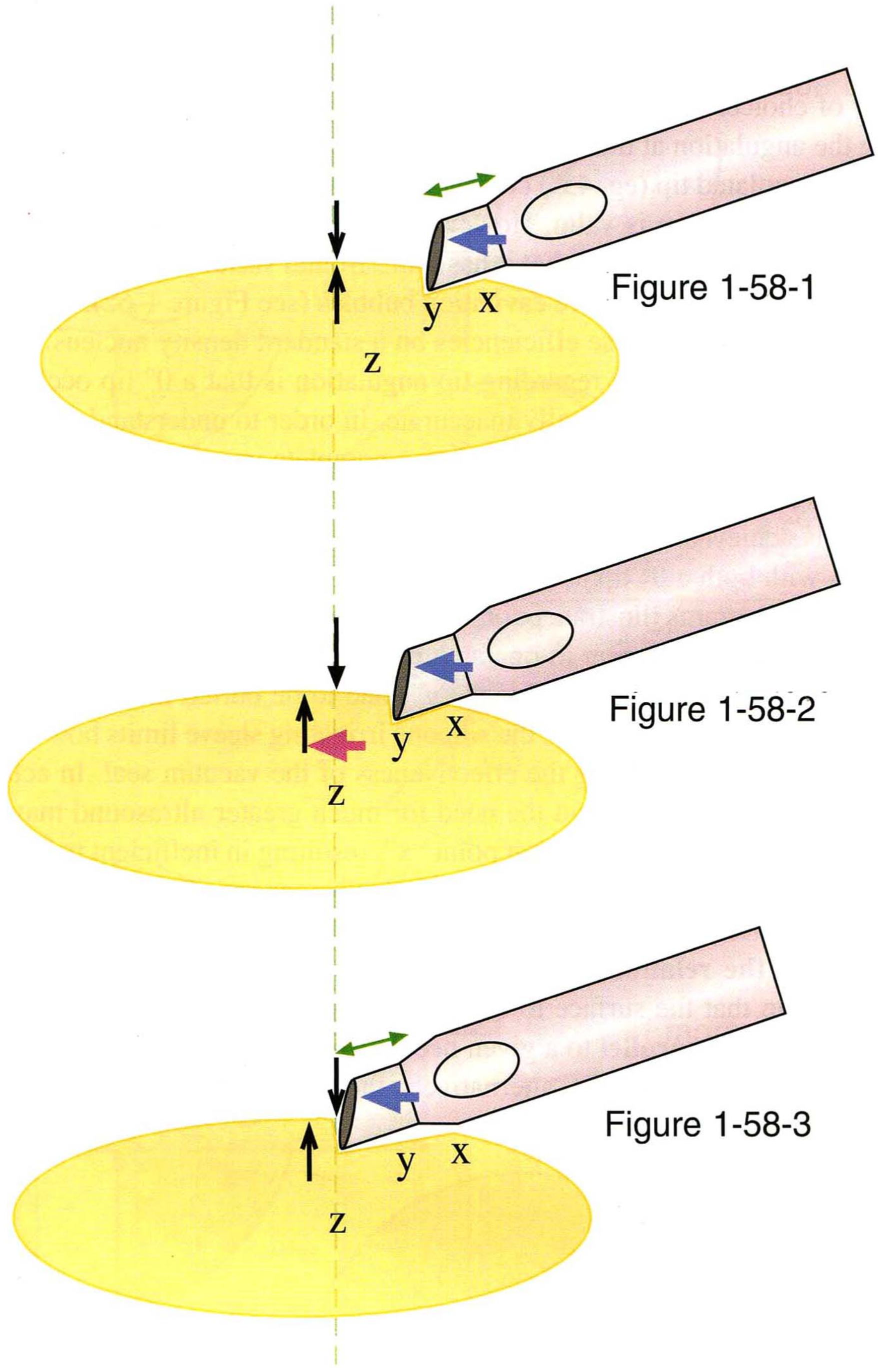


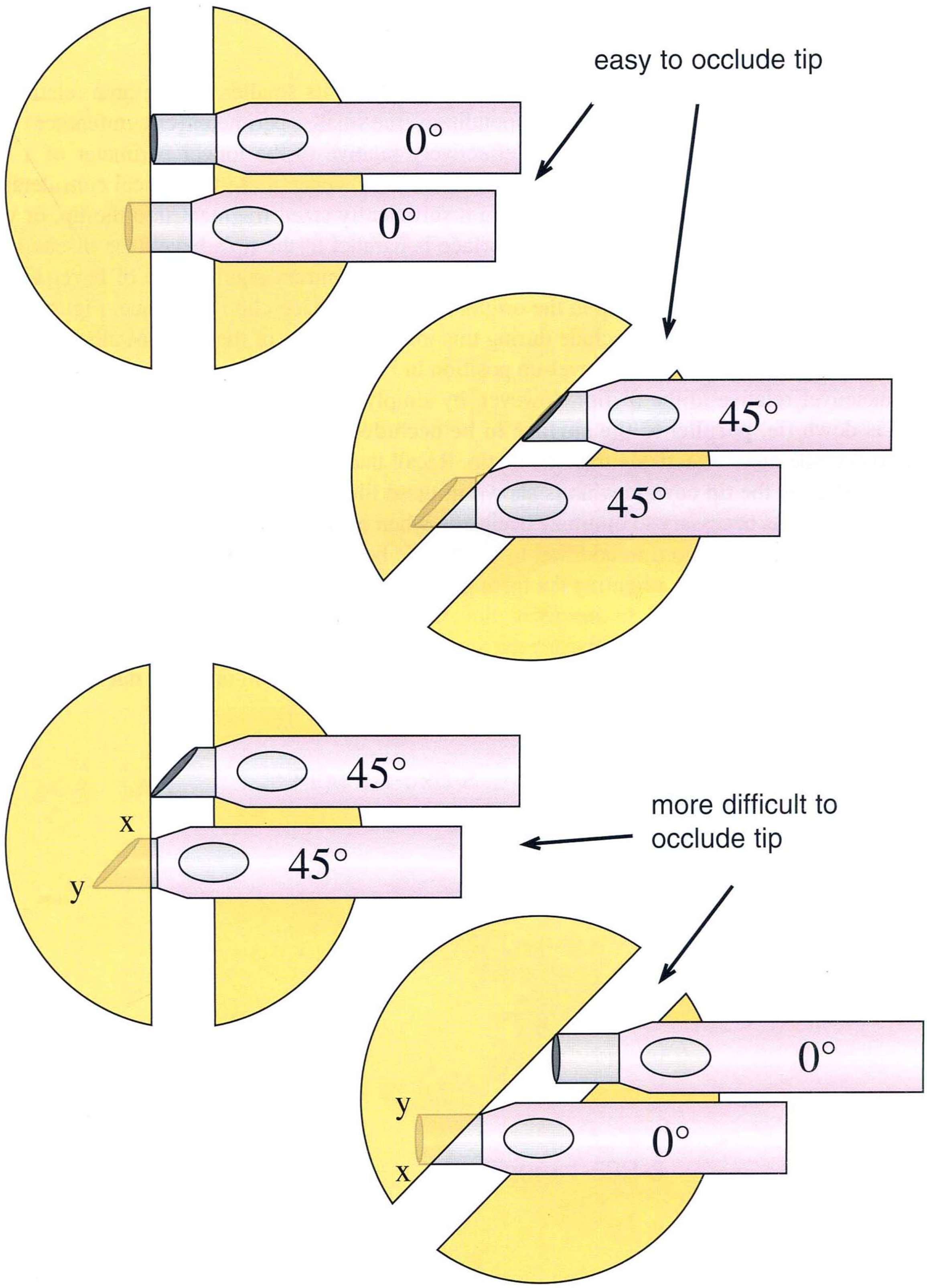
FIGURE 1-58

Phaco Needle Tip Angles: Occludability 1

A variety of choices exist with regard to ultrasonic needle design, with the most basic decision involving the angulation at the distal tip, illustrated in Figure 1-49. Traditional teaching mandates that a more angulated tip (eg, 45°) cuts or sculpts more effectively to the extent that the jackhammer mechanism of action is valid. However, microcavitation theory suggests that the 0° tip would be more efficient to the extent that it has more frontal surface area perpendicular to the axis of oscillation, thereby producing more cavitation bubbles (see Figure 1-62). In practice, it is difficult to quantitatively compare these efficiencies on a standard density nucleus.

Another traditional teaching regarding tip angulation is that a 0° tip occludes more readily than a 45° tip; this statement is generally inaccurate. In order to understand this concept, it is first necessary to define a good or **effective occlusion**: a complete impaling of the **aspiration port** into a given nuclear fragment such that the port is **uniformly embedded to an adequate depth** so that an effective grip is achieved. In Figure 1-59A, the upper two diagrams illustrate good occlusions as defined above with both a 0° tip as well as with a 45° tip.

The lower two diagrams illustrate poor, difficult, non-uniform occlusions; in order to achieve at least the same depth of occlusion in one area of the aspiration port (point "x") as in the upper drawings, the opposite side of the port (point "y") had to be buried much deeper, utilizing much greater ultrasound energy. Furthermore, the silicone irrigating sleeve limits how deeply the tip may be embedded, further compromising the effectiveness of the vacuum seal. In actual practice, the limitations of the irrigating sleeve and the need for much greater ultrasound may cause surgeons to stop short of fully embedding the port at point "x", resulting in inefficient transfer of the pump's vacuum and grip (see Figure 2-6-1) These difficult occlusions are illustrated with both a 0° tip and a 45° tip in Figure 1-59A. Therefore, the **bevel angle itself is arbitrary with regard to ease of occlusion**. However, **the relationship between the needle bevel angle and the surface to be engaged is critical** in that the surface to be engaged can and should be manipulated intraoperatively so that its surface is **parallel** to a given needle's bevel prior to attempted occlusion (see the upper two diagrams in Figure 1-59A); alternatively, the phaco handpiece can be rotated so that the bevel is parallel to a given surface.



easy to occlude tip
0°
0°
45°
45°
45°
x
45°
y
more difficult to
occlude tip
0°
y
0°
x

FIGURE 1-59A

Phaco Needle Tip Angles: Occludability 2

Theoretically, a 0° tip is easier to occlude because of its smaller surface area relative to a more beveled tip (see Appendix B). Correspondingly, the smaller perimeter (circumference) of the 0° aspiration port is more likely to seal effectively relative to the longer perimeter of a more beveled needle, assuming equivalent needle diameters. However, these theoretical considerations have less clinical relevance when carouseling a sufficiently sized fragment into the tip, or when embedding the tip into a fragment whose surface is parallel to the tip's bevel (see discussion of Figure 1-59A). Another relevant clinical example of the arbitrary significance of bevel angle to ease of occlusion is the initial step in the original Nagahara phaco chop technique. Figure 1-59B-2 illustrates how a 0° tip does occlude during this initial impaling of the nucleus, albeit just barely. The 45° tip in its conventional bevel-up position in Figure 1-59B-1 is seen to occlude poorly in this maneuver relative to the 0° tip. However, by simply rotating the 45° tip by 180° so that its bevel is down (ie, **parallel to the surface to be occluded**), as in Figure 1-59B-3, the 45° tip is seen to occlude more effectively than the 0° tip. Recall that the silicone sleeve is a physical barrier to embedding the tip beyond what is shown in these illustrations; therefore, it is imperative to rotate the bevel as necessary to optimize occlusion when burying the tip in a larger fragment prior to chopping or mobilization. In addition to the fluidic benefits of more readily obtaining a good occlusion and vacuum seal, orienting the tip angle so that it is parallel to the surface to be engaged has ultrasonic benefits as well. In this orientation, the emulsifying microcavitation bubbles are projected directly against (perpendicular to) the surface rather than at a less effective oblique angle, thereby further diminishing the need for excessive ultrasound to impale the nucleus (see also Figure 1-62).

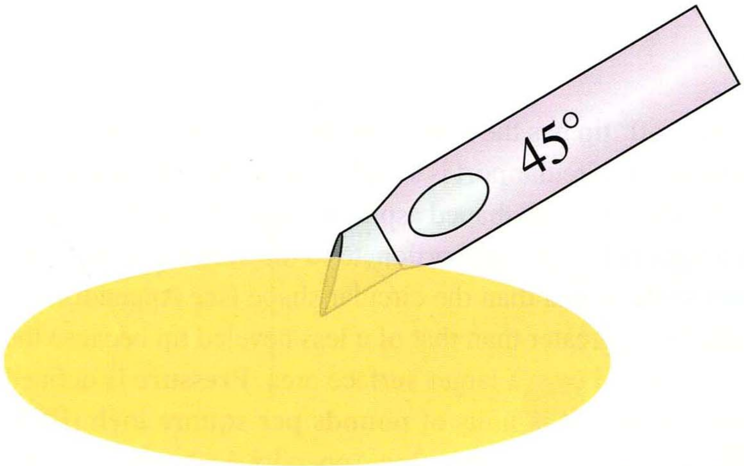


Figure 1-59B-1

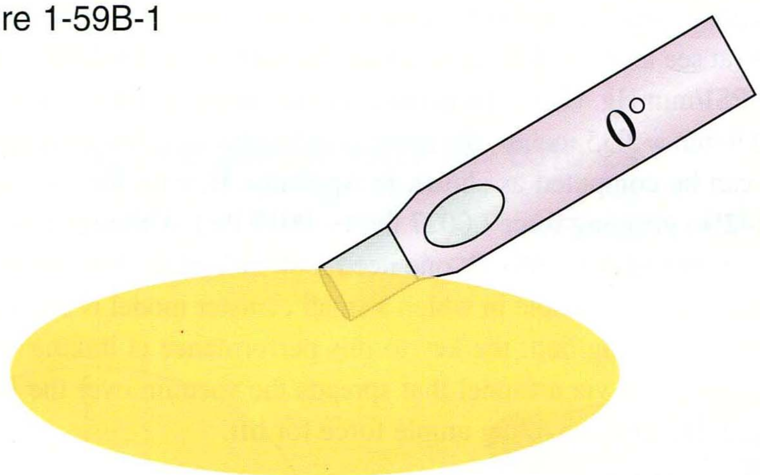


Figure 1-59B-2

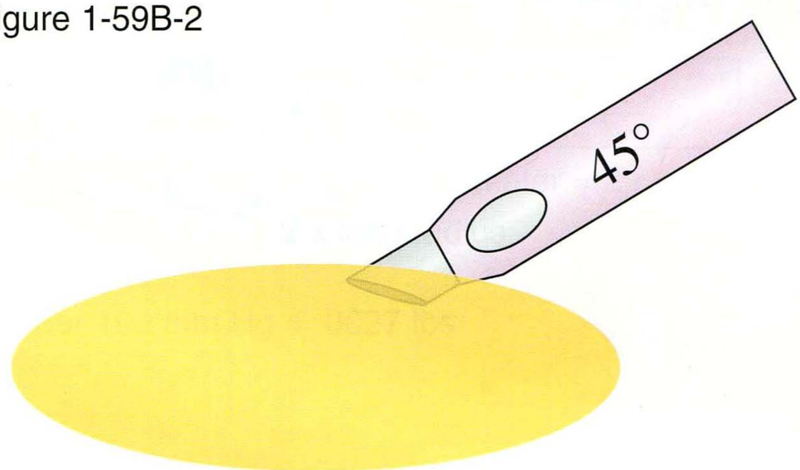


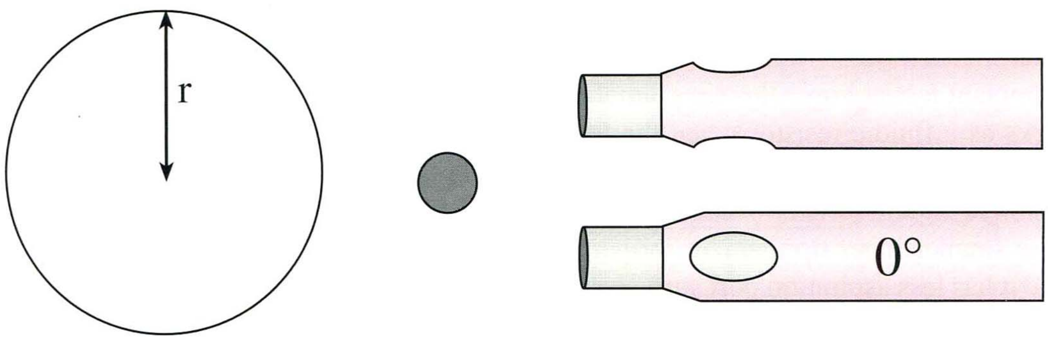
Figure 1-59B-3

FIGURE 1-59B

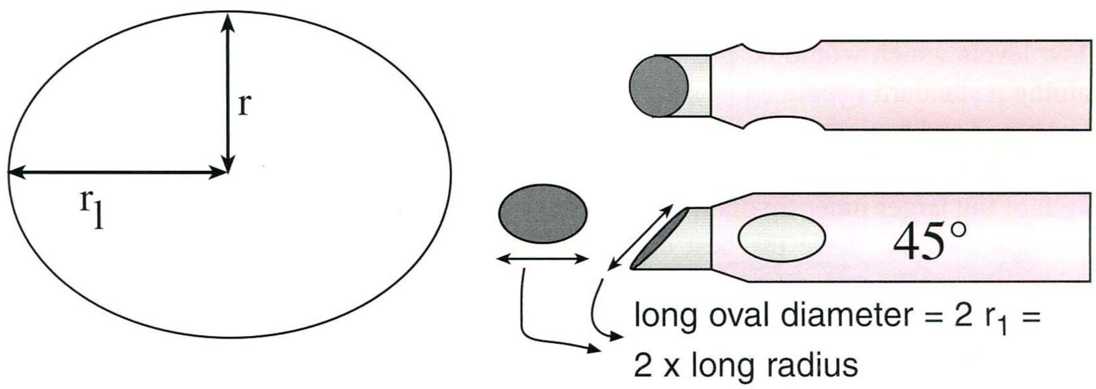
Tip Angles and Aspiration Port Surface Area

For a given ultrasonic needle diameter, a 0° tip has the minimum possible surface area for its aspiration port in that the uniform diameter of the circular port is simply that of the cylindrical needle's internal diameter (ID). An angled bevel has an oval-shaped aspiration port with a short radius being the same as a 0° tip, but having a longer radius (r_l) proportionate to the amount of the bevel (Figure 1-60); this oval shape has a larger surface area than the circular shape (see Appendix B).

The holding power of a more beveled tip is greater than that of a less beveled tip because the vacuum (negative pressure) of the pump is exerted over a larger surface area. **Pressure** is defined as the **force per unit area**, which is often expressed in units of **pounds per square inch (PSI)**. The units of mm Hg have an inherent surface area by definition (see Appendix A), but because the unit of surface area is not expressed, it will be useful to convert mm Hg to PSI for this illustration. Atmospheric pressure (at sea level) is defined as either 760 mm Hg or 14.7 PSI, which gives a conversion factor of .019 PSI/mm Hg. Using the derived surface areas of a 0° tip and a 45° tip, assuming a standard ID of 0.9 mm = .035 inches, the corresponding holding forces per unit vacuum (100 mm Hg in this case) can be computed as shown in Appendix B, with the greater bevel having a significantly greater (42%) gripping force (.0027 lbs vs .0019 lbs). Although this concept is rigorously mathematically proven in Appendix B, one need look no further than many vacuum cleaner commercials for a clear graphic example in which a small canister model is shown to have enough power to pick up a heavy bowling ball; the key to this performance is linking the small vacuum nozzle to the large bowling ball via a funnel that spreads the vacuum over the large surface area of the ball's hemisphere, thereby providing ample force for lift.



holding force per 100 mm Hg = .0019 lbs



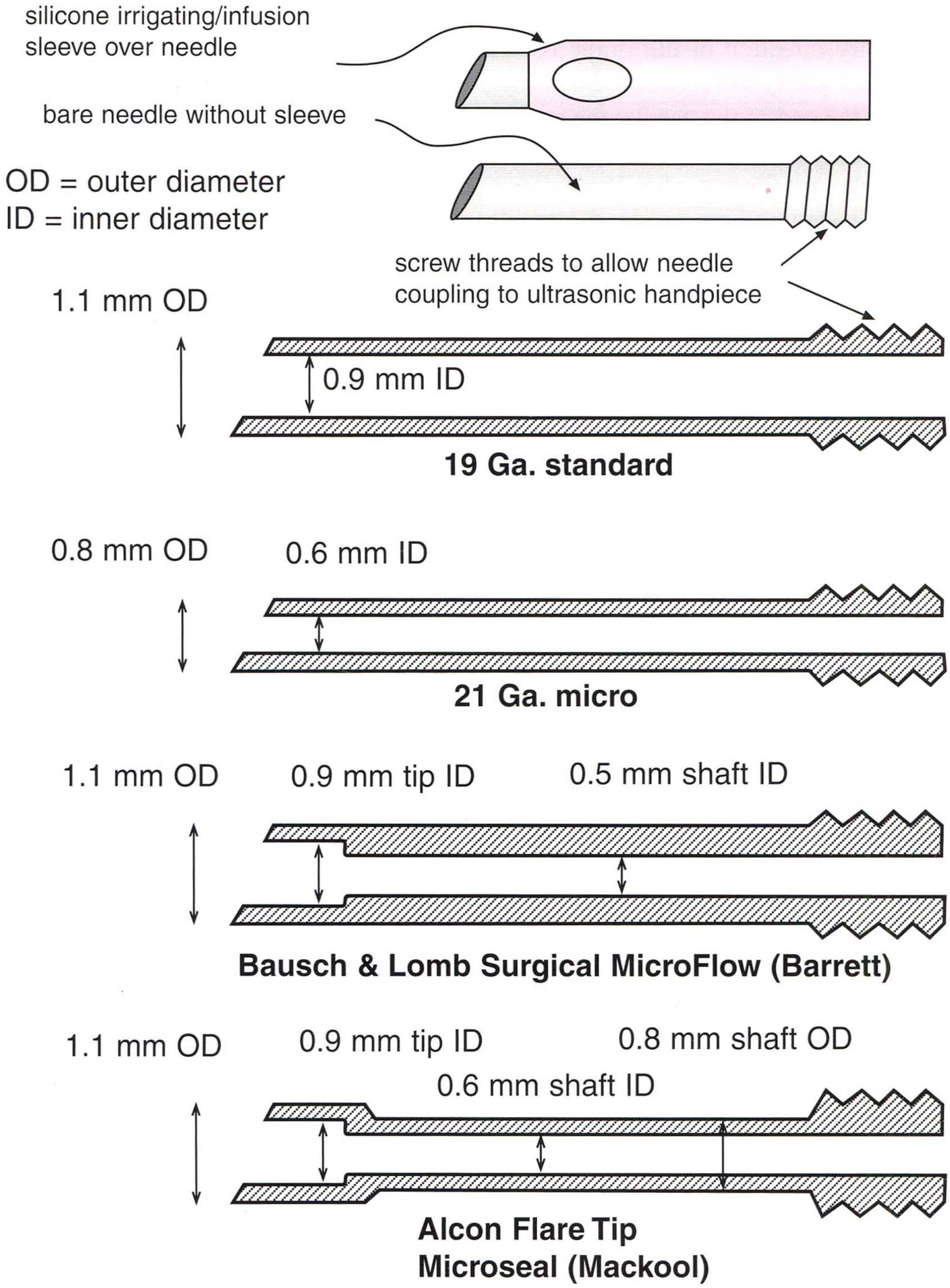
holding force per 100 mm Hg = .0027 lbs

FIGURE 1-60

Phaco Needle Dimensions

The various inner and outer diameter measurements of a phaco needle affect both its fluidic as well as mechanical performance. The original standard 19 Ga. phaco needle is shown toward the top of Figure 1-61 as a reference. By comparison, the 21 Ga. micro needle is seen to have both a smaller inner as well as outer diameter. The smaller outer diameter allows it to be used through a smaller incision; this will be an increasingly important attribute as advances in intraocular lens (IOL) implant technology allow implantation through smaller incisions. The smaller inner diameter works as a fluidic resistor when the tip is not occluded, decreasing the flow rate for a given pump setting relative to a standard needle, especially with vacuum pumps (see Figure 1-40a for discussion of fluidic resistors). Disadvantages of a smaller needle include the fact that upon occlusion, the smaller inner tip diameter provides less holding power for a given pump vacuum level because it has less aspiration port surface area relative to a standard tip (see discussion with Figure 1-60). Furthermore, even when using an efficient occlusion mode of phaco, less volume of nuclear material is removed (per unit time and level of ultrasound relative to a standard needle) simply because of the smaller volume that the 21 Ga. needle can accommodate.

The MicroFlow (Bausch & Lomb), Flare Tip (Alcon), and MicroSeal (Alcon) needles have a distal inner tip diameter identical to that of a standard needle; therefore, they will both have the same holding force for a given pump vacuum level when the tip is occluded. However, the smaller proximal shaft inner diameter provides similar fluidic resistance to that of the micro needle. This resistance is an advantage (especially with vacuum pumps) for the surgeon who desires a high vacuum level for nuclear manipulation and chopping but does not want the attendant dangerously high flow levels which would be present with an unoccluded standard tip. Another advantage of maintaining a standard needle's distal inner tip diameter is that more volume of nuclear material can be engaged and aspirated per unit time of ultrasound power application relative to a micro needle or any other design with a smaller inner tip diameter; this statement is valid in proportion to the length of the larger inner tip diameter distal to the smaller shaft inner diameter. These variable diameter tips therefore have the best characteristics of both standard and micro needles while diminishing the weaknesses of each.



silicone irrigating/infusion sleeve over needle
bare needle without sleeve
OD = outer diameter
ID = inner diameter
screw threads to allow needle coupling to ultrasonic handpiece
1.1 mm OD
0.9 mm ID
19 Ga. standard
0.8 mm OD
0.6 mm ID
21 Ga. micro
1.1 mm OD
0.9 mm tip ID
0.5 mm shaft ID
Bausch & Lomb Surgical MicroFlow (Barrett)
1.1 mm OD
0.9 mm tip ID
0.8 mm shaft OD
0.6 mm shaft ID
Alcon Flare Tip
Microseal (Mackool)

FIGURE 1-61

Ultrasonic Cavitation and Needle Design

The primary direction of ultrasonic oscillation is axial along the length of the needle, as shown in Figure 1-62 by the green arrows. Cavitation is usually limited to the area in front of the ring of metal at the end of the needle; the surface of this ring is roughly perpendicular to the long axis of the needle, allowing for any bevel angulation (see top illustration in Figure 1-62). Cavitation bubbles are formed when this surface pulls back from the distal excursion during each oscillation as a vacuum is created by the rapidly retreating surface; implosion of these bubbles occurs with tremendous energy and shock waves on a microscopic level, and is thought to be an important component of ultrasonic breakdown of lenticular material. According to Mark Schafer, PhD, bubble implosion occurs primarily during **transient cavitation**, which occurs at the onset of ultrasonic engagement. Transient cavitation quickly changes to **stable cavitation** with continuous ultrasound (and even standard Pulse and Burst Modes), and at this point the bubbles vibrate without imploding, thereby decreasing emulsifying efficiency. HyperPulse mode is thought to maximize transient cavitation and therefore enhance emulsifying efficiency by employing very short pulse durations.

Note that no cavitation is produced along the external shaft of the standard needle, which is oriented parallel to the direction of vibration and therefore does not encounter the distal ring's resistance to travel within the fluid medium (see dashed green arrow); similarly, no cavitation is typically produced within the lumen of the standard needle (dashed green arrow). Studies by William Fishkind, MD have illustrated directionality to emitted cavitation bubbles that coordinates with the needle's bevel angle (Figure 1-62). To protect the corneal endothelium during sculpting from the microcavitation stream of the 45° bevel as illustrated, the bevel could be turned posteriorly for sculpting; an even more effective protective measure would be to avoid sculpting in favor of the more efficient occlusion mode phaco (see Figure 1-50).

Cavitation can be augmented by modifications to the needle shape. The distal bend in the **Kelman needle** adds a nonaxial vibration (red arrow) to the primary oscillation (green arrow) which increases total cavitation at the tip relative to a standard tip with the same amount of ultrasound energy input (Figure 1-62). The nonaxial vibration further augments the axial vibration by producing an elliptical motion at the cutting tip which enhances mechanical breakdown of nuclear material. By incorporating additional angled surfaces which are roughly perpendicular to the long axis of the needle, the **Seibel tip** (MicroSurgical Technology) produces additional cavitation along the flat surfaces of the needle which are directed toward the distal tip as shown by the blue arrows. The Flare Tip, MicroFlow, and MicroSeal needles have an internal ring surface within the tip caused by the decrease from the distal tip's inner diameter to the main shaft inner diameter (see Figure 1-61); this inner ring surface is perpendicular to the axial direction of the needle and therefore produces additional cavitation. The **Cobra tip** has a similar design which produces additional internal cavitation.

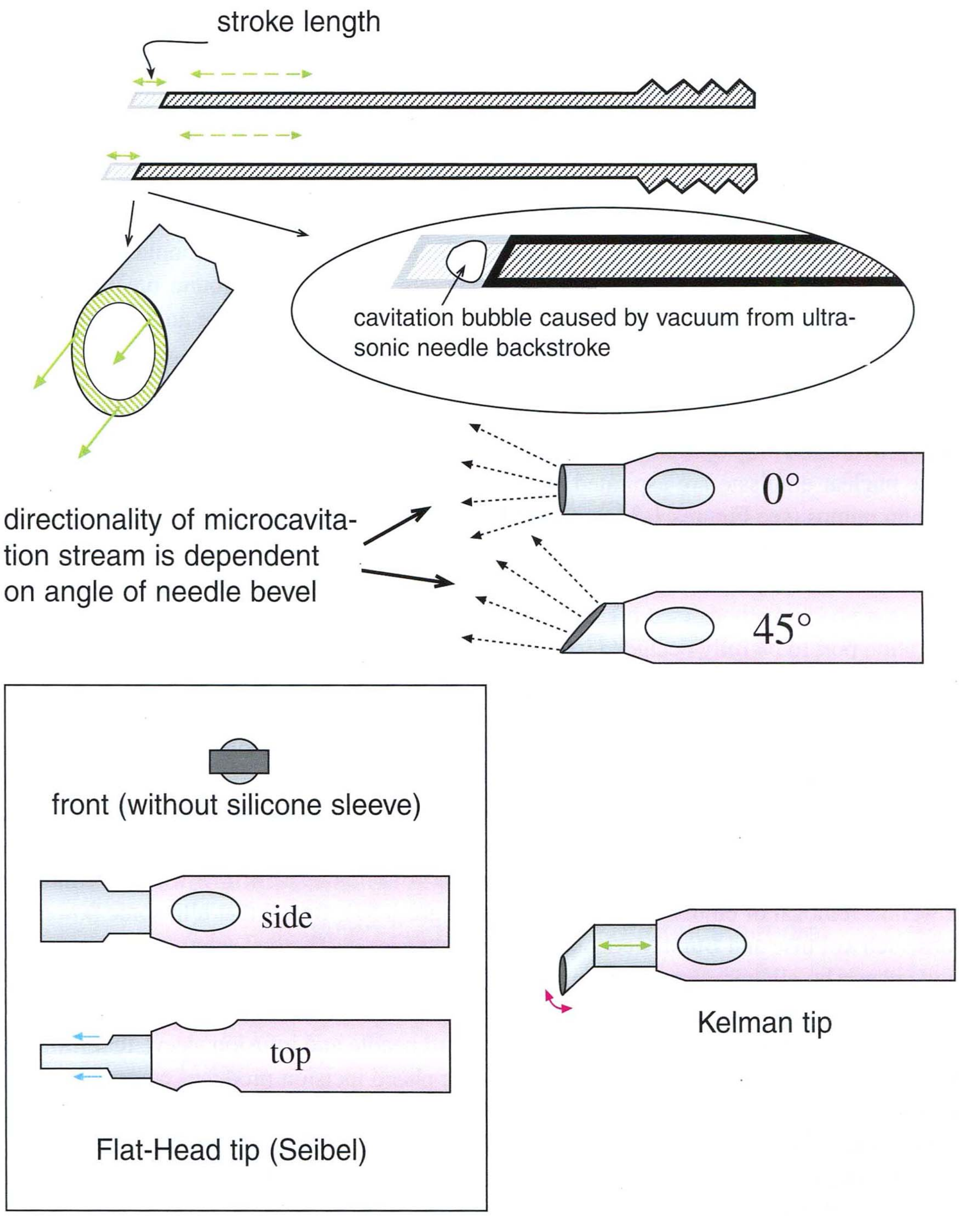

stroke length
cavitation bubble caused by vacuum from ultra-sonic needle backstroke
directionality of microcavitation stream is dependent on angle of needle bevel
0°
45°
front (without silicone sleeve)
side
top
Flat-Head tip (Seibel)
Kelman tip

FIGURE 1-62

Thermal Implications of Ultrasound: Needle Designs

With the needle vibrating at 20 to 60 kHz, potentially dangerous heat can build up from two sources in direct proportion to the ultrasound power (stroke length) and the duration for which it is applied. First, friction from the needle shaft's oscillation in aqueous as well as distal cavitation can produce increased temperature, usually at a slow to moderate rate. Second, friction at the point of the silicone sleeve compression against the ultrasonic needle by the surgical incision can sometimes rapidly increase temperature to the level of protein denaturation, resulting in a wound burn. Both sources can be influenced by surgical technique. For example, one should avoid maintaining high ultrasound power for long continuous intervals. Unnecessary wound pressure can be prevented by avoiding handpiece positions which result in lifting or extreme angulations at this location.

Fluidic parameters can influence heat production by affecting flow rate; less heat is produced to the extent that more anterior chamber fluid exchange and more fluid flow around the needle shaft provides cooling. Recall that aspiration line fluid becomes more viscous as viscoelastic and dense nuclear emulsate are aspirated, and that flow is consequently diminished, especially with vacuum pumps (see Figures 1-34 and 1-40B); machine parameters should be adjusted accordingly. One should especially avoid maintaining high ultrasound power while the aspiration port is occluded and thus prohibits any cooling flow; however, this caveat does not preclude the use of occlusion phaco methods (see Figure 1-50). For example, some chopping maneuvers require the aspiration port to be fully occluded to effectively build vacuum and gripping power (see Figure 1-30), but this can be accomplished by a brief application of moderate ultrasound to embed the tip, followed quickly by a return to pedal position 2 to titrate vacuum appropriately without any further ultrasound until the chop is completed. Furthermore, occlusion methods of carouseling do not necessarily produce excessive heat even though ultrasound power is maintained for mildly to moderately sustained periods; the reason is two-fold. First, only mild to moderate levels of ultrasound are required because of the greater efficiency of occlusion methods (see Figure 1-50). Second, full occlusion is rapidly and intermittently interspersed with moments of flow which facilitate cooling as well as removal of emulsified material (see Figure 1-57). Recall that ultrasonic power modulations such as Pulse and Burst Modes will further increase the thermal safety profile with occlusion mode phaco by allowing some cooling during rest intervals (Figures 1-55 and 1-56).

Different needle designs have been developed to decrease the likelihood of wound burns (Figure 1-63A); note the cross-section of a standard needle and infusion sleeve that shows contact between the two at the top and bottom, where the phaco incision produces compression and subsequent friction during ultrasonic vibration. The Alcon Flare Tip ABS keeps a larger volume of cooling irrigating fluid around the small diameter shaft; this is further facilitated by the High Infusion Sleeve that resists collapse against the needle by the incision. Furthermore, the ABS (Aspiration Bypass System) port allows a small amount of continued cooling flow (blue arrow) even when the distal tip is completely occluded. Dr. Richard Mackool's MicroSeal design incorporates an insulation sleeve between the needle and the infusion sleeve.

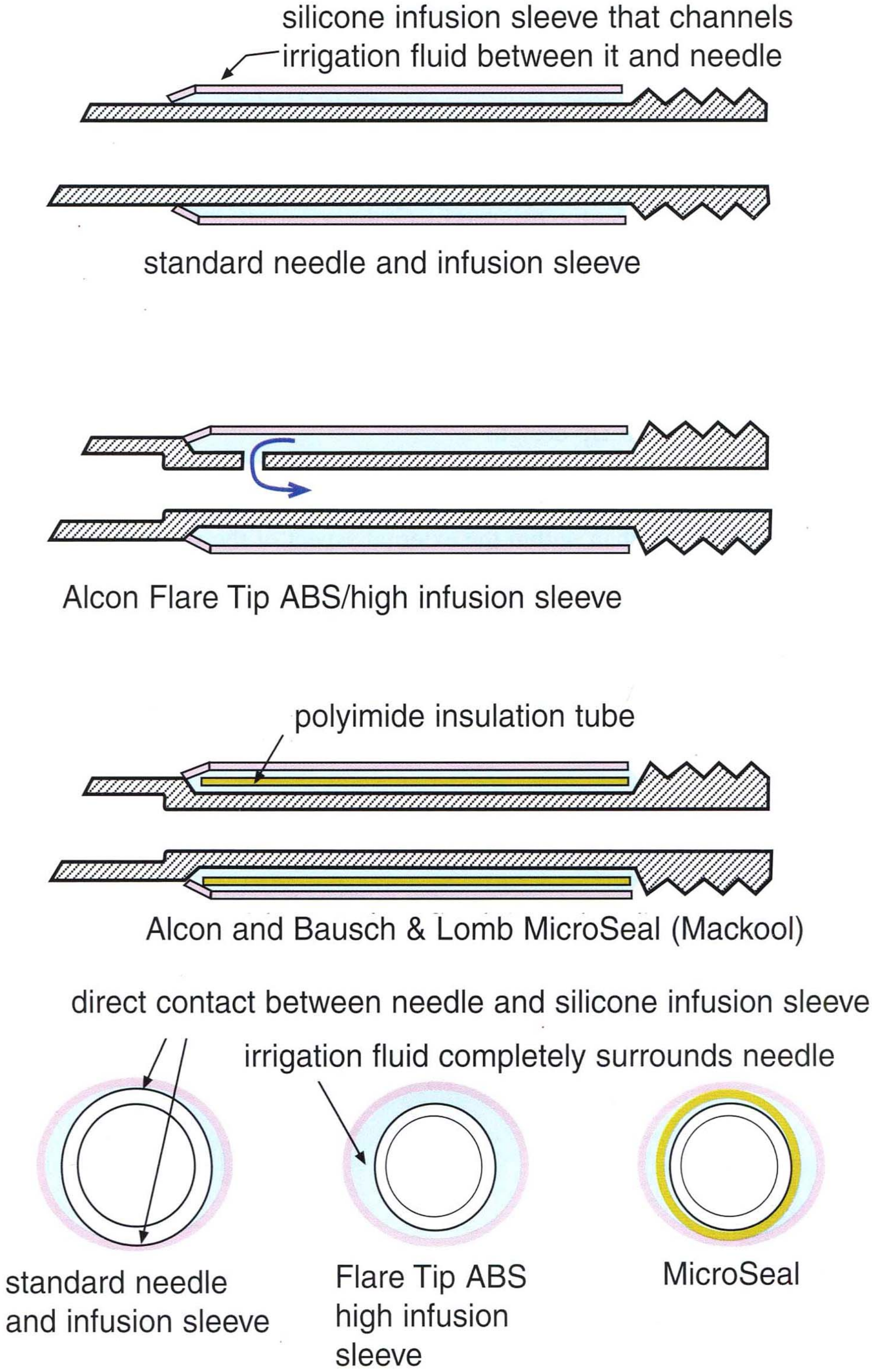

silicone infusion sleeve that channels irrigation fluid between it and needle
standard needle and infusion sleeve
Alcon Flare Tip ABS/high infusion sleeve
polyimide insulation tube
Alcon and Bausch & Lomb MicroSeal (Mackool)
direct contact between needle and silicone infusion sleeve
irrigation fluid completely surrounds needle
standard needle and infusion sleeve
Flare Tip ABS high infusion sleeve
MicroSeal

FIGURE 1-63A

Thermal Implications of Ultrasound: Needle Designs (continued)

The risk of an incisional burn is decreased to the extent that cooling irrigation fluid can dissipate excess heat that was produced by friction from the vibrating ultrasonic needle within the surgical wound, as discussed with Figure 1-63A. Another design that facilitates this goal is the MicroFlow needle (Bausch & Lomb) designed by Graham Barrett, MD. The majority of its length has external longitudinal grooves that continue to channel cooling irrigation fluid even when the silicone sleeve is compressed against the needle by incisional pressure. This portion of the shaft has to be thicker to accommodate the grooves, resulting in a smaller lumen that has the fluidic benefits of surge resistance. Because grooves are not needed at the very distal portion of the tip, this section can have a larger inner diameter to facilitate a stronger grip for a given amount of vacuum, as discussed for the Alcon Flare Tip design.

This same concept of channeling grooves of cooling fluid around the needle is manifest in reverse by the Surgical Design approach, which places the grooves within the inner surface of the silicone infusion sleeve rather than within the external aspect of the phaco needle. Of course, the standard 19 Ga. needle shown with it does not have the fluidic benefits outlined above for the dual-lumen size MicroFlow needle.

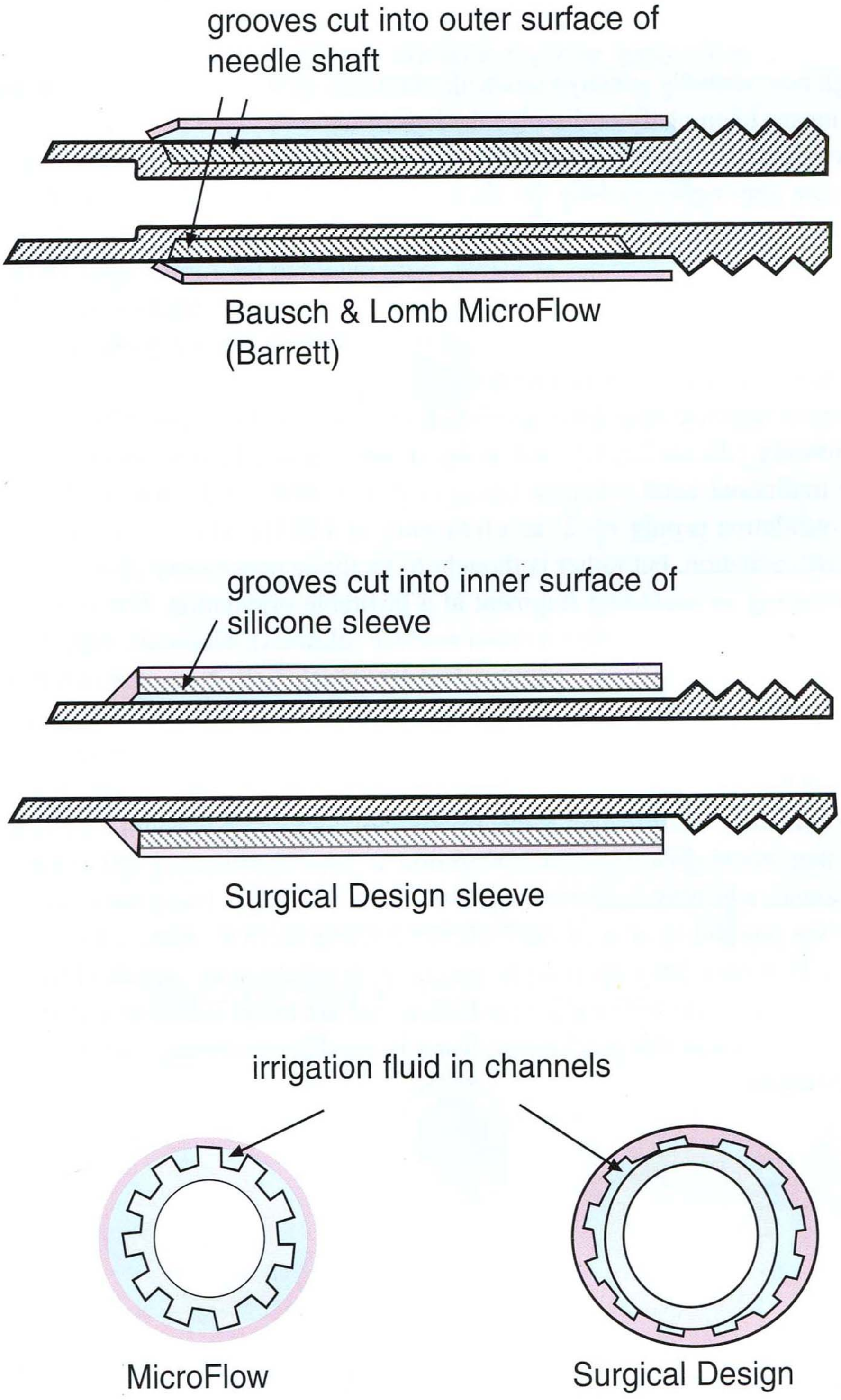

grooves cut into outer surface of needle shaft
Bausch & Lomb MicroFlow (Barrett)
grooves cut into inner surface of silicone sleeve
Surgical Design sleeve
irrigation fluid in channels
MicroFlow
Surgical Design

FIGURE 1-63B

Alternate Modalities of Phacoemulsification: Ultrasound Variations

Although now virtually synonymous with ultrasonic technology, the word **phacoemulsification** literally means to emulsify or dissolve the lens of the eye. In the past decade other modalities have been investigated as potential alternatives to ultrasonic phacoemulsification. Important goals in these alternate approaches include the ability to overcome the historical problem of the ultrasonic tip's heat generation as well as to provide for the possibility of endocapsular emulsification when an injectable gel IOL becomes available. With regard to the former goal, HyperPulse mode ultrasonic phacoemulsification (a.k.a. "**cold phaco**", a term originated by David Chang, MD), promises to preempt the new laser technology by facilitating thermal protection to the incision with ultrasound (see discussion with Figure 1-56).

One group of alternate modalities involves modifications of the basic ultrasonic platform. For example, **NeoSonix** (Alcon Legacy and Infiniti) adds an oscillatory component (curved blue arrow) to the traditional axial vibration (straight green arrow) of the needle (Figure 1-64). The amplitude of oscillation is only +/- 2° at a frequency of 120 Hz. This low level of vibration does not produce any cavitation, but rather is thought to facilitate progressive phacoaspiration by continuously reengaging an occluding fragment at a favorable orientation. For very soft nuclei (eg, predominantly posterior subcapsular without nuclear sclerosis), Neosonix may be used without ultrasound to assist vacuum-driven aspiration. For denser cataracts, Neosonix may be set to engage at a percentage of maximum oscillation once a threshold level of ultrasound has been reached. The greatest effect of this oscillation is appreciated with a Kelman tip; compare the front views of a standard and a Kelman tip in Figure 1-64 with regard to the greater tip excursion in the latter.

Another ultrasonic modification is the invention of Alex Urich; he built a handpiece (**STAAR Sonic Wave**) that would drive the needle vibration at lower frequencies (40 to 400 Hz) as compared to ultrasound, which by definition is greater than 20,000 Hz. These lower frequencies virtually eliminate the possibility of incisional friction causing thermal injury, and readily adapt this equipment to a Bimanual Microincision technique with a bare sonic needle (Figure 1-2). These low frequency vibrations do not produce cavitation, and are better suited to soft to moderate densities of cataracts, although this machine platform is capable of offering traditional ultrasound as well for denser nuclei.

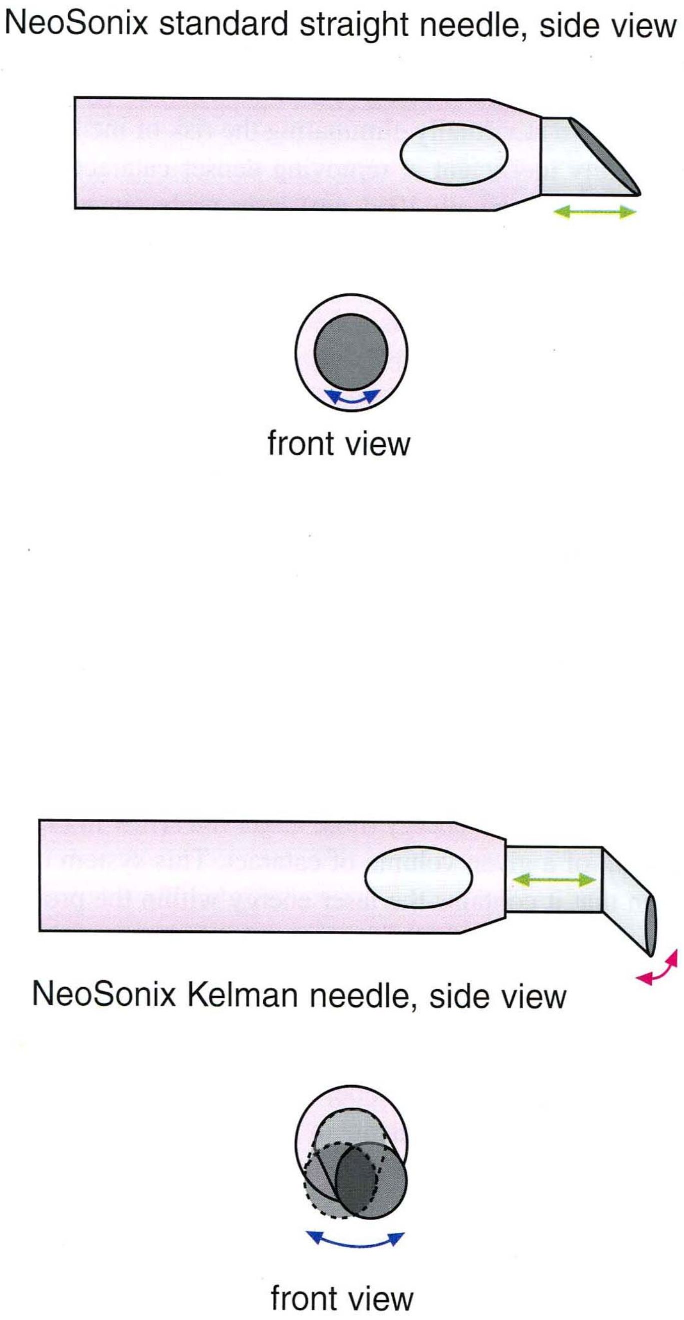

NeoSonix standard straight needle, side view
front view
NeoSonix Kelman needle, side view
front view

FIGURE 1-64

Alternate Modalities to Ultrasound: Laser

As opposed to a vibrating ultrasonic tip that produces potential friction and heat at the incision, the various machine platforms that incorporate laser technology feature fixed, nonvibrating laser probes. Although effective at virtually eliminating the risk of incisional burns, all of the laser phaco platforms are relatively inefficient at removing denser cataracts. The Dodick Q-switched Neodymium:YAG (Nd:YAG, wavelength 1064 nm) laser probe, invented by Jack Dodick, MD, focuses its laser energy (red arrow in Figure 1-65-1) on a titanium target within the distal tip of the probe. This target allows the laser energy to form plasma at lower energy levels than would be required without the target. The plasma causes optical breakdown and subsequent shock waves (green curved lines) to emanate from the probe's distal tip in order to facilitate acoustic breakdown of lens material, which is then aspirated within the probe's central lumen (blue dashed arrow). The titanium target is therefore acting as a transducer, converting laser energy to acoustic energy but without a vibrating ultrasonic needle with its attendant thermal implications. The design confines laser energy to within the probe, protecting both the eyes of the patient and the surgeon. One probe houses the aspiration and photolysis functions, while a second irrigating probe is used in a Bimanual technique.

The Paradigm Medical Industries machine (Figure 1-65-2) also confines its Nd:YAG beam to within the distal probe, but without the use of Dr. Dodick's titanium transducer, the surgeon must actively draw lens material into the laser gap in the probe as opposed to the greater ergonomic flexibility of having emulsifying sound waves emanate a short distance from the tip. Also, without the lowered threshold for plasma formation afforded by a titanium target, the Paradigm system theoretically would require more laser energy (note larger red arrow in Figure 1-65-2 relative to 1-65-1) for photovaporization of a given volume of cataract. This system does share the advantage of Dr. Dodick's design in that it contains the laser energy within the probe for safety, and it may have a further advantage of reliability with a simpler probe without moving parts or a titanium target. Like the Dodick design, aspiration of disrupted lens material occurs via the central lumen (blue arrow).

The Asclepion-Meditec Phacolase unit employs an Erbium:YAG laser (wavelength 2940 nm) that emits energy from the smooth distal probe, resulting in photoacoustic breakdown of lens material. Although the laser emission (red arrow in Figure 1-65-3) is not contained within the tip as in the Dodick and Paradigm systems, the Erbium:YAG absorption in water is 1000 times greater relative to Nd:YAG energy and is therefore confined effectively to the area immediately around the tip. The combination of the emission of emulsifying energy longitudinally from the tip, the presence of a central coaxial aspiration path (blue arrow), along with the availability of a coaxial infusion sleeve (not illustrated), make this modality familiar to a surgeon accustomed to sculpting with ultrasound. Additionally, the Erbium:YAG laser surgeon may employ a separate irrigation probe in a Bimanual technique, as well as an alternate infusion pathway such as an anterior chamber maintainer.

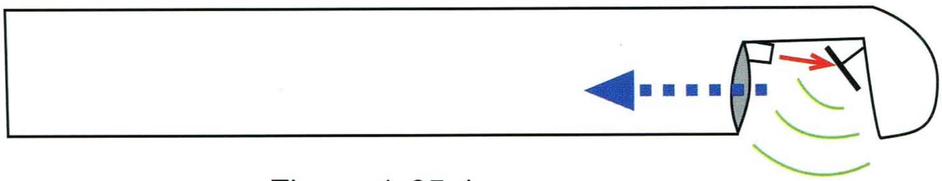


Figure 1-65-1


Figure 1-65-2

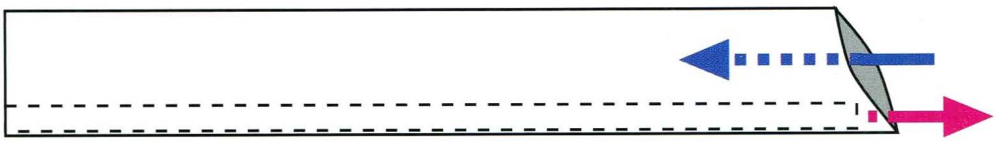


Figure 1-65-3

FIGURE 1-65

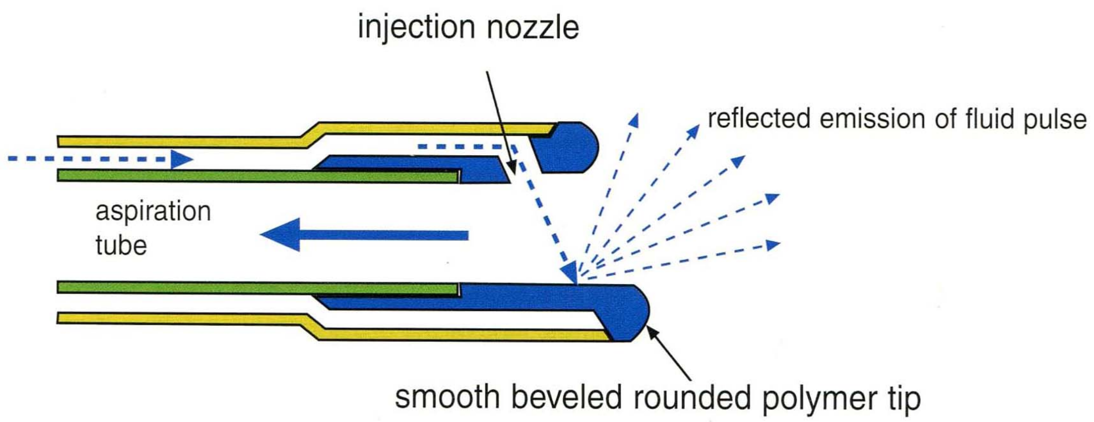

injection nozzle
reflected emission of fluid pulse
aspiration
tube
smooth beveled rounded polymer tip

FIGURE 1-66

Irrigation and Aspiration Tips

After the ultrasonic handpiece and tip are used to remove the lens nucleus and epinucleus, the surgeon usually changes to the slimmer nonultrasonic **Irrigation and Aspiration (IA)** handpiece and tip as illustrated in Figure 1-67. The IA tip is ideal for removing the gelatinous or diaphanous cortex as well as any residual viscoelastic. In particular, IA vacuuming of the posterior capsule has been shown by David Apple, MD to be a significant deterrent to postoperative posterior capsule opacification. As opposed to the denser and often more crystalline nuclear material, the cortex and any viscoelastic do not require ultrasonic breakdown in order to be aspirated (see also Figure 1-51). The standard IA tip's aspiration port size (diameter) is 0.3 mm, which is much better suited than the larger phaco aspiration port (typically 0.9 mm per Figure 1-61) to being occluded by the often thin layer of cortex. Even though the high resistance IA port can produce significant vacuum without occlusion (especially with higher flow rates, as in Figure 1-41), full occlusion allows full transfer of the pump's vacuum to the occluding cortex (see Figures 1-11 and 1-30 for the same principle with occluding nucleus) and is therefore more efficient when sufficient cortical volume and structure allows occlusion.

The irrigation sleeve is similar to that of the phaco handpiece, although it is available in metal as well as silicone. The IA tip differs from the phaco tip as illustrated, being smooth and rounded with a single aspiration port usually located on the side of the tip, not at the end. The sleeve may be turned to orient the irrigation ports in any direction, but it is usually most efficient to place them as shown, each 90° away from the aspiration port. If one irrigation port was in the same orientation as the aspiration port, the irrigating fluid would tend to push away the material to be aspirated.

In addition to the straight tip, 45°, 90°, and 180° tips are available to allow more versatility in accessing difficult areas of cortex (ie, subincisionally). One handpiece design allows the tips to be quickly interchanged using an O-ring/twist-lock attachment. Another option is the Alcon Silicone IA tip, a major advance in safety that virtually precludes the possibility of capsule rupture during capsule polishing from a metal burr in the aspiration port. The metal aspiration port and tube are safely encased by a silicone tip that incorporates its own 0.3 mm aspiration port.

As opposed to the fixed silicone tip of the Alcon Design, Ed Zaleski of AMO designed a flexible silicone tip that can be transformed from a straight configuration through an entire range of curved configurations by sliding the sleeve controller as illustrated in Figure 1-67. A similar version of the tip was conceived by Dr. Charles Kelman and offered on the Alcon Legacy platform; this design included a footswitch controller that controlled the tip configuration changes under the protection of continuous irrigation (recall discussion with Figure 1-3). All of these silicone tip designs share the advantage that the tip is made of silicone instead of metal, and its transparency allows visualization of cortex within the tip as aspiration is taking place, thus providing valuable additional visual feedback, especially at times when the aspiration port is not optimally visible.

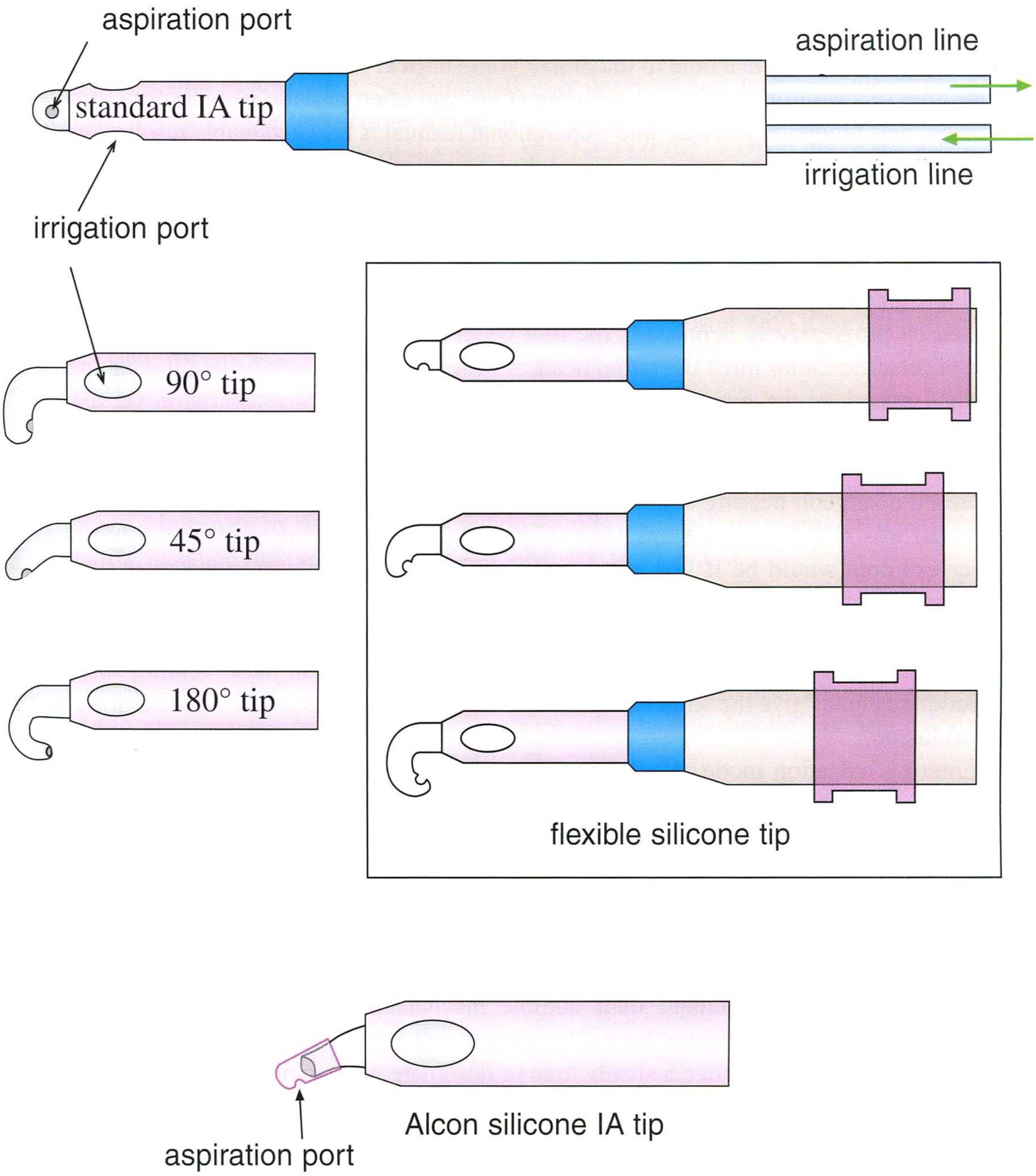

aspiration port
standard IA tip
irrigation port
aspiration line
irrigation line
90° tip
45° tip
180° tip
flexible silicone tip
Alcon silicone IA tip
aspiration port

FIGURE 1-67

Individual Machine Characteristics

Know your machine! Although this book describes the fundamental characteristics shared by many phaco machines, each particular company's machine has unique features. You must be aware of all features of a given machine to maximize your surgical options and to take full advantage of the machine's capabilities. Company representatives can often provide very comprehensive information on their products. The machine's operational manual is also a valuable resource and should be considered required reading.

All machines give audible feedback during their operation; it is important to understand and be aware of these sounds during surgery. Many sounds are secondary to the mechanical operation necessary for a given function. For example, the sound of releasing compressed gas is present on venturi machines in position 2 or 3; furthermore, it is noted to become more intense as vacuum is increased by progressively depressing the foot pedal with linear control. A peristaltic pump will hum as its electric motor turns the pump head. A faster pump flow results in a louder and/or higher pitched sound as the pump head turns faster. Occlusion during aspiration on a peristaltic machine will often give an intermittently irregular cessation to the humming sound as the machine vents to keep the vacuum at the level selected by the combination of foot pedal position and vacuum preset; a surgeon hearing this noise, for example, might elect to increase the vacuum preset if the pedal was fully depressed and cortical/epinuclear material was engaged but not aspirating. Another example would be if you hear the machine venting while engaged in position 2 even though the aspiration port is not visibly occluded; this usually indicates an obstruction somewhere in the aspiration line which will require checking the line for kinks and perhaps trying to dislodge any occult material by refluxing into a test chamber. In addition to these venting sounds, many flow pump machines give the surgeon additional feedback in the form of an audible tone that indicates occlusion.

Entering irrigation mode almost always produces a metallic click as the plunger that was pinching the irrigation tubing is snapped into the open position. Engaging ultrasound power always produces a buzzing sound, the intensity of which increases with increasing power. Recall that this sound is not ultrasound but rather the sub-harmonic tones of the handpiece and needle; the increasing intensity is secondary to the increasing amplitude of the stroke length caused by increasing power. Tactile feedback during ultrasound power application is present in the form of subtle vibration in the handpiece, which also increases with increasing power.

Many machines supplement their audible mechanical feedback with various electronic sounds. A particular machine may have a beeping sound for IA, which increases in frequency as vacuum increases. It may utilize a steady tone to designate ultrasound application. As mentioned above, some machines produce a tone to indicate occlusion of the aspiration port, often sensed by the machine's actual vacuum reaching the preset limit. Some machines allow user modification of these electronic feedbacks with regard to type and intensity of sound for a given function.

The foot pedal offers valuable tactile feedback. Some simple mechanical units feel identical in both phaco and IA modes, giving detents between positions 1, 2, and 3. More elaborate electromechanical models override a detent in IA mode so as to combine positions 2 and 3 into a single larger pedal excursion in position 2. Some models may not have any detents; some of these may have uniform resistance for their entire travel, while others may have progressively increasing resistance with increasing depression of the pedal. Several AMO units allow the surgeon to opt for the pedal to vibrate in between positions. You should note the actual machine readings for a given pedal position by putting a test chamber on the phaco handpiece while observing the machine panel during pedal operation. For example, with a phaco preset maximum of 100% and linear pedal control, one machine might yield 50% actual power with the pedal depressed halfway into position 3, whereas another machine might produce 75% actual power with its pedal halfway into position 3. Linearity and responsiveness of the foot pedal during vacuum and flow changes may also be observed in the same manner.

Through awareness of these various feedback sounds and proprioceptive feedback during normal machine operation, the surgeon can make logical choices about altering parameters according to visual feedback through the operating microscope, without turning to look at the machine panel readings. Moreover, by understanding which sounds and feels are normal, the surgeon may readily identify machine malfunctions when the feedback is abnormal.

When reading your machine's manual, pay attention to the section on setup. It is the surgeon's responsibility to know more about the equipment than anyone else in the operating room. If your regular scrub technician is unavailable one day, your patients must not be compromised because of a substitute scrub tech's lack of familiarity with your machine. Knowledge of proper machine setup also proves invaluable when intraoperative troubleshooting is necessary. Many problems may be traced to kinked or improperly connected tubing.

SECTION TWO

Logic of Setting Machine Parameters

Overview of Logic Behind Setting Machine Parameters

In order to appropriately adjust the machine parameters for various stages of surgery, it is necessary to analyze the function of those parameters for a given stage. This approach obviates the need for memorization of ponderously large and arbitrarily arranged tables of settings, and it allows the surgeon to spontaneously adapt to changing surgical conditions by visual feedback through the operating microscope. For example, sculpting requires proper titration of ultrasound power so that the phaco needle carves the nucleus without excessively displacing it and stressing zonules. Furthermore, sculpting requires only enough flow to clear the anterior chamber of the emulsate produced by ultrasound as well as sufficient flow to cool the phaco tip. There is little need for vacuum during sculpting; there are not yet any fragments which need to be occluded and gripped. Furthermore, high vacuum is not needed to counteract the repulsive action of ultrasound since the nucleus is held stationary by the capsule, zonules, and its intact structure at this point. However, a modest level of vacuum (eg, 60 mm Hg) does help to prevent clogging of the aspiration line when sculpting denser cataracts.

Once the nucleus is debulked or grooved by sculpting, it often needs manipulation such as rotation or cracking. These maneuvers should be performed in pedal position 1 or in continuous irrigation mode so that the chamber will be adequately deep and pressurized but without any pump action which might inadvertently aspirate unwanted material. Once the nucleus is debulked or cracked into fragments, machine parameters need to adapt to the needs of emulsifying these fragments. Ultrasound power requirements are lower at this stage relative to sculpting because of the increased efficiency of phacoaspiration with complete or almost complete tip occlusion (see Figures 1-50 and 1-57). However, flow rate and vacuum usually must be increased from their sculpting levels in order to overcome the repulsive action of ultrasound at the axially vibrating needle tip on a free-floating chopped fragment. As fluidic levels of flow and vacuum are increased, bottle height must be correspondingly raised to insure chamber stability such that infusion may keep up with higher outflow levels. These parameters of fluidics and ultrasound should ideally be linearly and independently titrated intraoperatively for a given degree of nuclear density and fragment configuration. This level of control has only recently been available to the surgeon with the advent of Dual Linear Pedal control as previously described.

Chopping maneuvers often require further manipulation of parameters. A horizontal chop may require only moderate vacuum because the nucleus is mechanically fixated between the phaco tip and the chopper. However, higher vacuum levels can be used advantageously to grip and manipulate the nucleus. For example, the gripped nucleus can be displaced so that the chopper is more centrally located when engaging the nuclear periphery. This maneuver is especially effective if the nucleus was previously grooved and hemisected as has been described by Drs. Paul Koch and Ronald Stasiuk (see Figures 2-15 and 2-16A). Higher vacuum levels are also useful when gripping and manipulating quadrants in preparation for emulsification, and vertical chopping typically requires higher vacuum levels than horizontal chopping. The higher vacuum levels require appropriate caution in order to prevent surge problems, including attention to bottle height. Figures 1-48-1 through 1-48-4 address this issue.

Although specific parameter values will be given in this section of the book, it is crucial to remember that these are only a baseline guide. Recall from Section One that the panel setting on a given phaco machine can produce variable results depending on numerous factors. For example, vacuum degrades in the aspiration line when the aspiration port is not completely occluded (see Figure 1-42); therefore, for a given panel preset vacuum level, the actual attractive force at the phaco tip will vary according to the aspiration line length as well as the degree to which the aspiration port is occluded. Similarly, flow can be set directly on a flow pump (by choosing a panel preset pump speed) or indirectly with a vacuum pump (by choosing a panel preset vacuum level); however, the actual flow through the aspiration port will vary according to the degree of aspiration port occlusion as well as the size of the aspiration port and the inner diameter of the phaco needle (see Figures 1-11, 1-29, and 1-40A). Actual flow will also vary intraoperatively secondary to changing viscosity in the aspiration line as variable amounts of viscoelastic and emulsified nucleus are aspirated (Figure 1-34); recall that vacuum pumps are especially sensitive to fluidic resistance (see Figure 1-40B). Because actual values of flow and vacuum can therefore vary considerably on different machines with similar settings, the baseline setting suggestions in this section must be adjusted according to visual intraoperative feedback as will be described. When relevant in this section, flow pumps and vacuum pumps will be differentiated with regard to parameter settings; however, recall that once the aspiration port is occluded, the effect of setting vacuum limit (flow pump) is identical to setting commanded vacuum (vacuum pump). In other words, the uniform hydrostatic pressure (vacuum) in the aspiration line between the pump and the occluding nuclear fragment will be the same whether it was produced by a vacuum pump or by a flow pump.

Anterior Chamber Currents

A conceptual framework of anterior chamber fluid dynamics is necessary in order to apply the principles outlined in Section One. At the most basic level, the intraocular current is simply a function of the location of the irrigation and aspiration ports as depicted in Figures 2-1-1 and 2-1-2. Intraocular fluid as well as free-floating particles are drawn along the current lines toward the unoccluded aspiration port when in foot position 2 or 3. A faster flow rate will produce a stronger current (see Figure 2-1-2) than a slower flow rate (see Figure 2-1-1). Current strength can be increased with a flow pump by simply increasing the flow rate parameter. Because there is no independent flow rate adjustment on vacuum pumps, current strength is increased by increasing the commanded vacuum, which correspondingly increases flow rate with an unoccluded aspiration port.

Changing the vacuum limit preset on a flow pump will generally not affect the flow rate; an exception would be setting a low vacuum preset with a high resistance 0.3 mm IA tip. In this instance, most peristaltic machines would be incapable of high flow rates because of intermittent pump cessation and/or venting when the vacuum preset was reached at low to moderate flow rates (see discussions with Figures 1-11 and 4-1). These schematic currents (purple lines) of course represent an ideal laminar flow environment whereby free-floating material is drawn toward the aspiration port. In reality, some turbulence and **eddy currents** (blue spiral lines) are produced because of incisional leakage as well as variable anterior chamber fluid viscosity due to suspended lens particles, air bubbles, and viscoelastics. These eddy currents can be responsible for sub-optimal followability in which nuclear fragments are not readily drawn toward the aspiration port despite a flow rate setting that would otherwise be adequate.

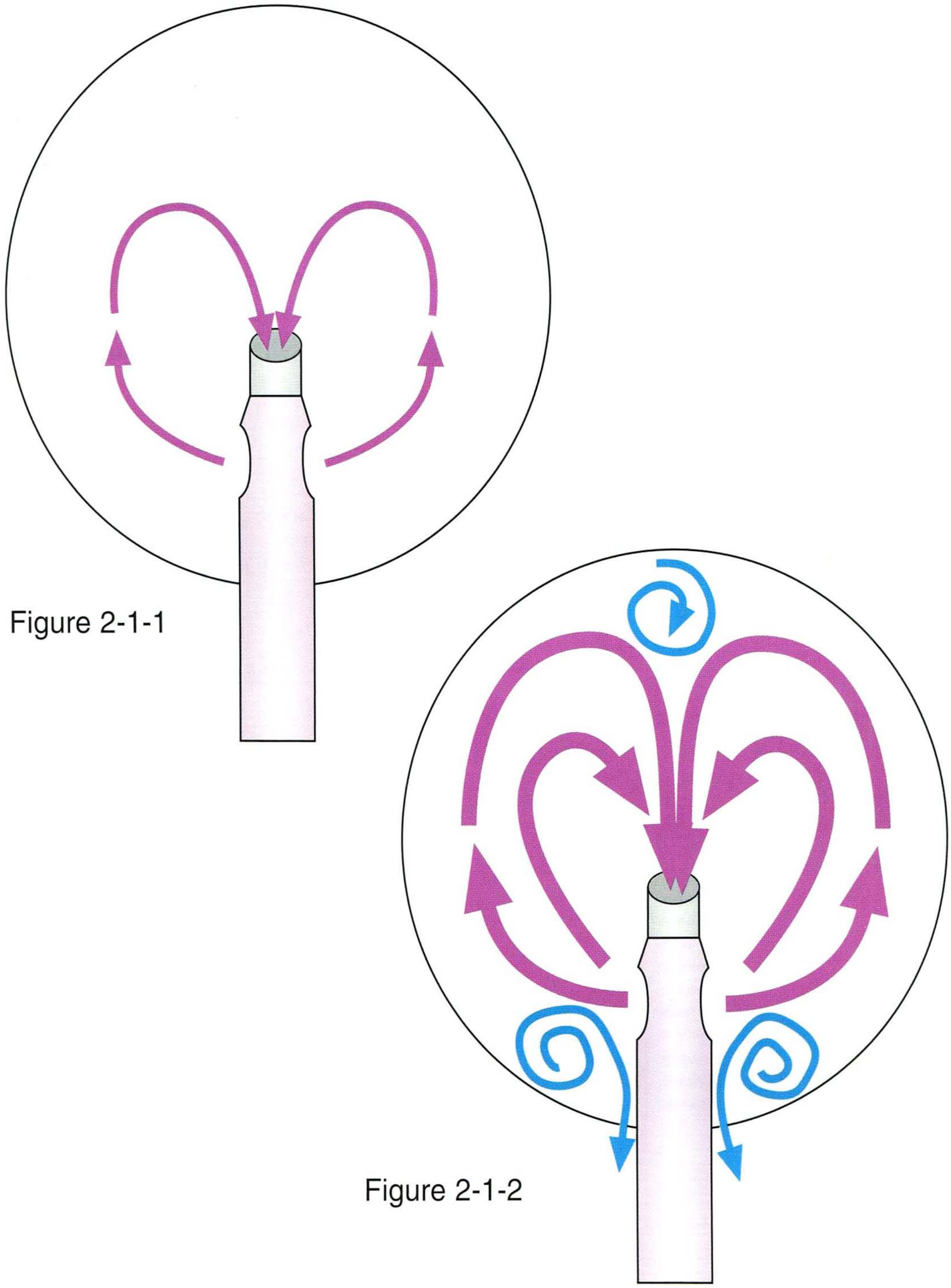


Figure 2-1-1

Figure 2-1-2

FIGURE 2-1

Flow Rates and Currents

These illustrations attempt to quantify anterior chamber currents with regard to flow rate. For example, Figure 2-2-1 shows three purple dots per row flowing through the phaco tip per unit time, which is represented as the distance between the rows of dots. Each dot may be thought of as a quantum or unit volume of fluid. Therefore, you can think of this schematic as representing a flow rate of three quanta per unit time, or perhaps 30 cc/min. Correspondingly, Figure 2-2-2 represents 50 cc/min (five dots or quanta per row). Note that as the distance from the tip increases, the density and speed of the current diminishes because the three or five quanta per row are drawn from an increasing area or volume of intraocular fluid. This phenomenon is analogous to a river in which a wider, deeper section has a slower, gentler current than does a narrower, shallow section which must transfer the same volume as the larger section in the same amount of time, thus producing the stronger current.

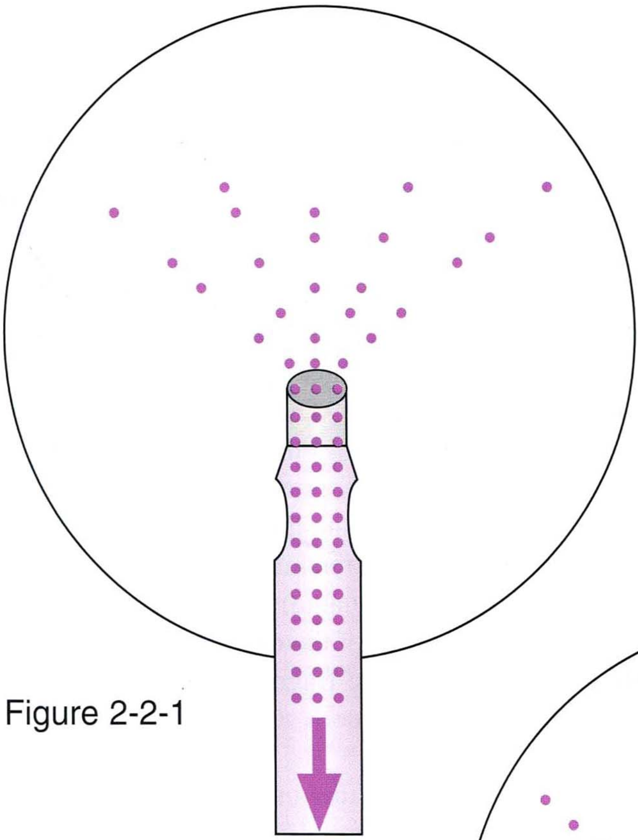


Figure 2-2-1

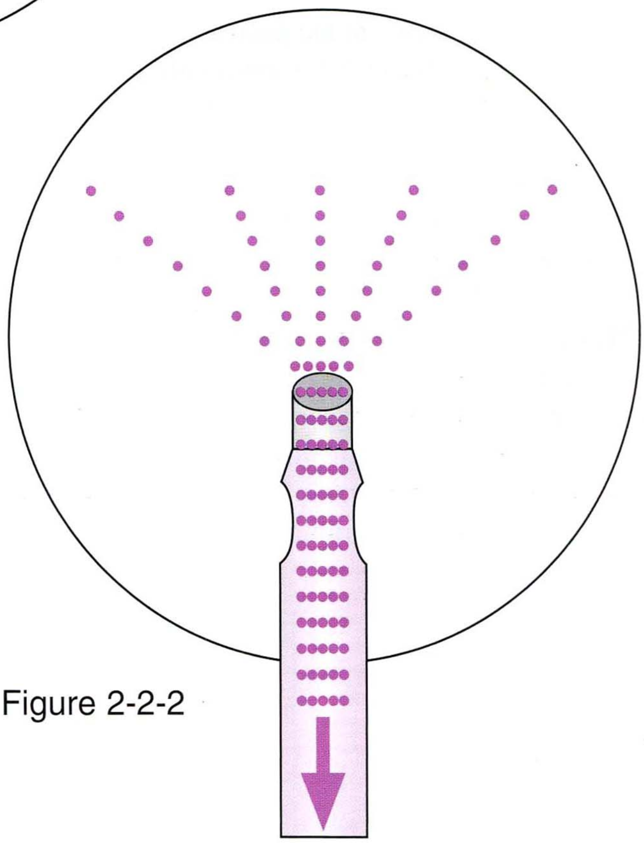


Figure 2-2-2

FIGURE 2-2

Force and Currents

The anterior chamber current, which is directly proportional to the aspiration flow rate, is the force which draws intraocular fluid and any suspended lens particles or fragments into the aspiration port. The current is propagated on a microscopic level by the moving water molecules pulling adjacent molecules by intermolecular attraction and friction while pushing adjacent molecules by collision and friction. These forces can be schematically represented by the quanta of fluid (**purple dots**) exerting a pushing force on a suspended fragment (**red bar**) as they travel into the aspiration port. In Figure 2-3-2 (50 cc/min), the fragment when located right at the tip has five quanta of fluid/force pushing it into the tip. Contrast this with only three quanta of force pushing the corresponding fragment into the tip in Figure 2-3-1 (30 cc/min). Therefore, increasing the flow from 30 cc/min to 50 cc/min increases the force pushing (drawing) the fragment into the port by almost 70% (three quanta increasing to five quanta). When the fragment is 1.5 mm from the tip, the higher flow rate still draws the fragment more strongly than the lower flow rate (three quanta of pushing force as opposed to two quanta). However, the differential between flow rates is less at this distance from the tip (50% increase from two to three quanta) than when the fragment is right at the tip; this is due to the decreasing speed and strength of the current with increasing distance from the tip. This effect is especially prominent when the fragment is 3 mm from the tip, where in these two schematics an identical one quantum of force is exerted despite the different flow rates.

Several important clinical corollaries can be drawn from this information. First, more **followability** (attraction to and into the aspiration port) can be exerted on intraocular fragments by increasing the flow rate; this effect is more prominent closer to the tip. Second, to exert more attraction farther away from the tip, especially 3 mm or more, flow rate has to be raised considerably. However, recall that very fast flow rates can decrease your safety margin by quickly drawing in potentially unwanted material (iris and capsule) as well as allowing less reaction time for reflux because of the corresponding rapid rise time (Figure 1-13). Furthermore, this attractive force will be exerted in all directions following the circular currents (see Figure 2-1) and the conical distribution of the schematic quanta. Therefore, greater control can be achieved by using more moderate flow rates and working in the area closer to the tip.

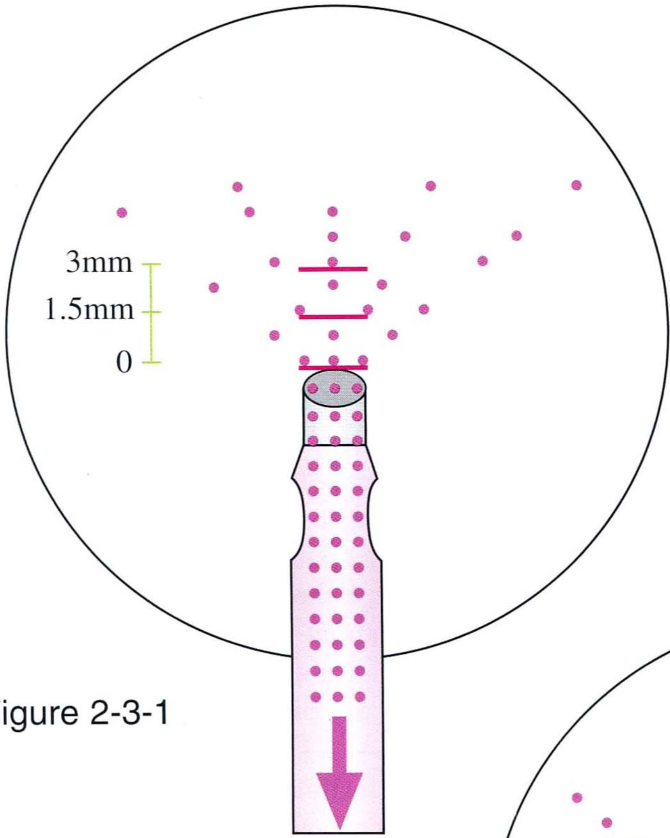


Figure 2-3-1

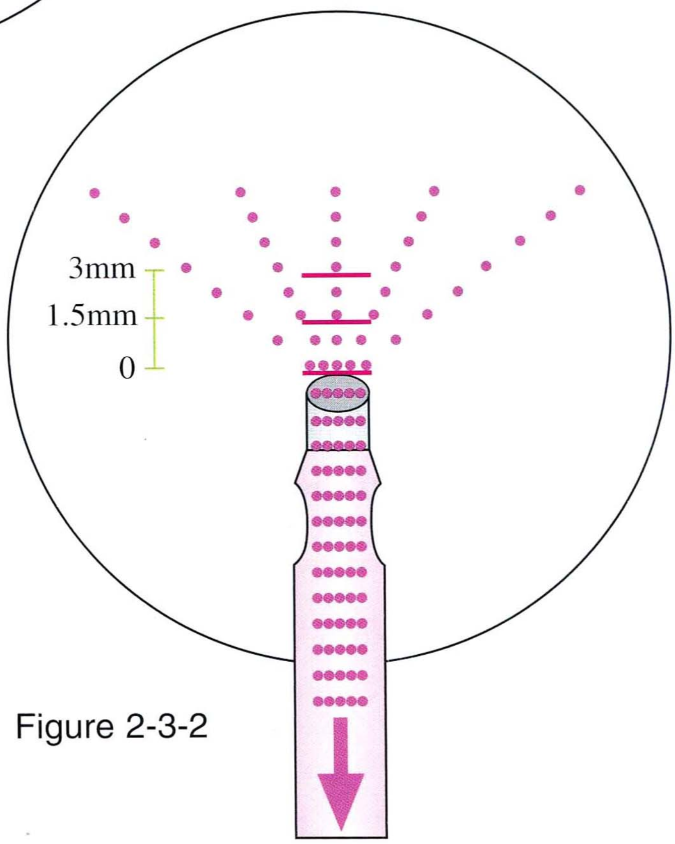


Figure 2-3-2

FIGURE 2-3

Flow and Vacuum Settings 1: Distal Followability

In order to place the foregoing schematics in a more clinical perspective, we will now look at a scenario in which we wish to attract the final nuclear segment after a chopping procedure. Moreover, we will determine when flow and vacuum are relevant parameters at various intraoperative stages. **Aspiration flow rate** (cc/min) determines how strongly fluid and fragments are attracted toward the unoccluded aspiration port (**distal followability**). Once a fragment occludes the aspiration port, vacuum (mm Hg) determines how strongly it is held to the aspiration port. **Therefore, the degree of aspiration port occlusion is a vital clinical determinant of which parameters are pertinent at a given moment in surgery**.

For example, in Figure 2-4, let's assume a flow pump machine with a flow rate of 18 cc/min and a vacuum preset of 100 mm Hg. If the quadrant were entirely free-floating, this low flow rate would probably be sufficient to attract it to the tip. However, if the quadrant were not readily moving toward the tip (ie, because of residual nuclear or epinuclear adhesions), then an appropriate adjustment would be to increase flow rate in order to produce a stronger current and therefore a stronger attraction (a surgeon using a vacuum pump could at this point increase commanded vacuum in the drainage cassette, which would increase flow through the unoccluded tip as in Figure 1-28). Alternatively, the tip could be moved closer to the quadrant, recalling that the current is stronger closer to the tip (see Figure 2-3). Note that even though the vacuum limit preset is 100 mm Hg, the actual vacuum just inside the tip is minimal because of the negligible resistance to flow from the large bore phaco needle (see Figures 1-28 and 1-41). Therefore, increasing the vacuum limit preset level on a flow pump in this scenario would not enhance attraction; it would simply change the vacuum preset reading on the panel (green bar) without affecting the fluidics. Recall that a flow pump's vacuum preset limit only determines the level to which actual aspiration line vacuum will rise given sufficient resistance to flow, usually with occlusion of the aspiration port (see Figure 1-11). If Figure 2-4 represented a vacuum pump instead of a flow pump, then increasing the commanded vacuum level would increase attraction of the fragment to the tip by the corresponding increase in flow rate (recall Figure 1-28; recall also the difference between commanded vacuum with a vacuum pump and vacuum limit with a flow pump defined in Figures 1-8 and 1-25). Recall that **bottle height** must be increased to maintain anterior chamber depth and pressure if aspiration outflow is increased.

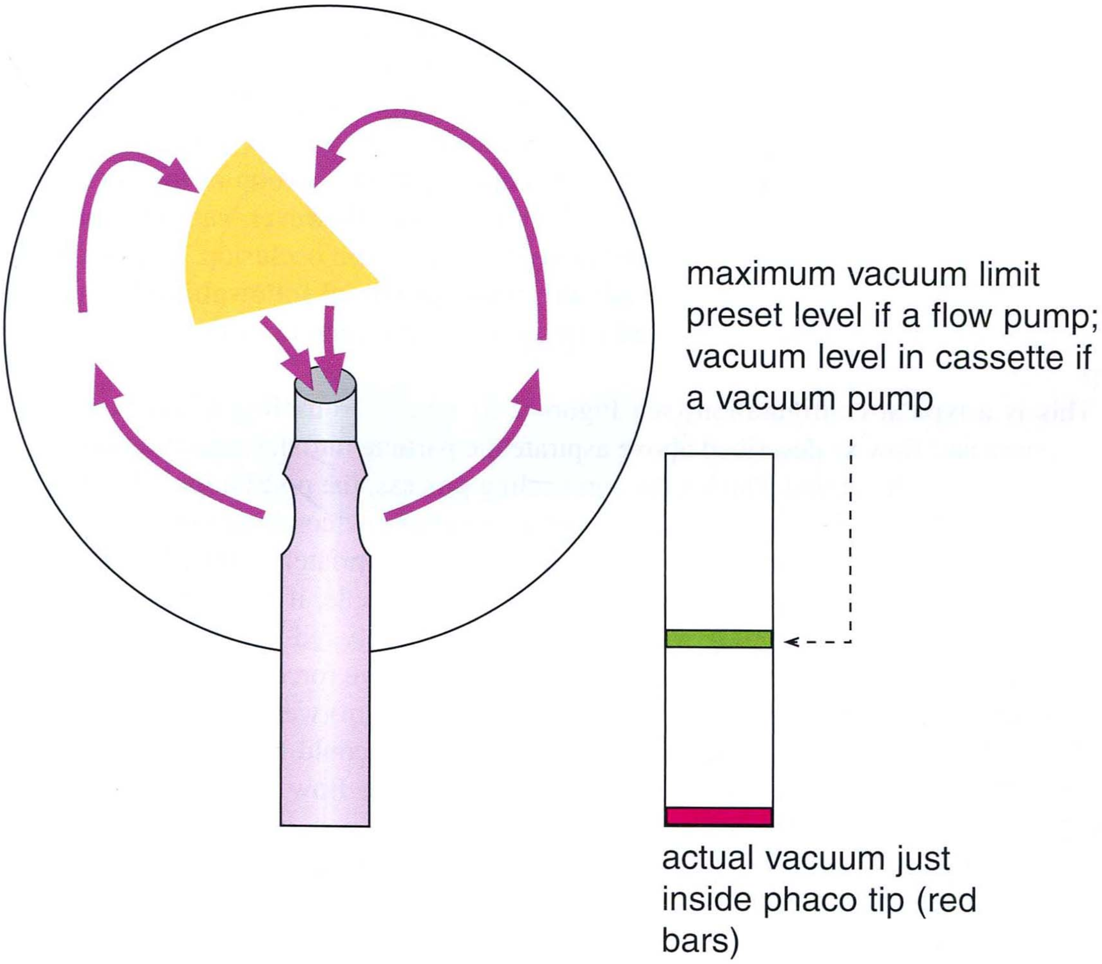

maximum vacuum limit preset level if a flow pump; vacuum level in cassette if a vacuum pump
actual vacuum just inside phaco tip (red bars)

FIGURE 2-4

Flow and Vacuum Settings 2: Proximal Followability

In Figure 2-5, ultrasound energy (pedal position 3) has been used to embed the tip into the nuclear fragment such that approximately two thirds of the aspiration port is occluded. Flow still exists through the unoccluded portion of the port, albeit at a reduced rate (see Figure 1-11). This flow still functions to pull the fragment onto the tip although with less force than the higher flow in Figure 2-4. To the extent that the pump's force is not directed into flow production, it builds vacuum as it pulls fluid through the increased resistance of the smaller effective surface area of the aspiration port; the vacuum (holding force) is applied to the portion of the nuclear fragment that occludes the aspiration port (see Figures 1-11 and 1-41). However, vacuum cannot build up to the full preset limit of 100 mm Hg in the absence of complete occlusion. The **combination of vacuum and flow** contributes to the overall attraction (**proximal followability**) of the fragment into the tip, especially against any applied ultrasound which tends to push fragments away from the tip.

This is a typical configuration (see Figure 2-5) when carouseling a fragment into the tip while vacuum and flow as described above aspirate the particle into the aspiration port against the repulsive action of ultrasound. During the carouseling process, the port rapidly alternates between complete and partial occlusion, with vacuum or a vacuum/flow combination contributing to followability, respectively. These fluidic forces must be appropriately titrated to the amount of applied ultrasound as well as to the nuclear density. For example, if the nuclear fragment in this illustration was dense and chattering without being progressively fed into the tip, then the machine parameters would need to be adjusted so that either the repulsive force was decreased (ie, decreasing ultrasound power) or the attractive forces (flow and vacuum) were increased. If a flow pump is used, then both the flow rate and the vacuum limit preset could be increased to enhance followability. With a vacuum pump, which has no independent flow rate control, only the commanded vacuum level could be increased, although this effectively increases flow as well during the instances of partial occlusion as the fragment carousels into the tip. Indeed, this **autoregulation** of vacuum and flow (according to the degree of port occlusion) is a relative advantage of a vacuum pump (or mode) over a flow pump with regard to optimizing followability because the surgeon only needs to titrate a single fluidic parameter (commanded vacuum) to achieve a clinical goal (increased proximal followability).

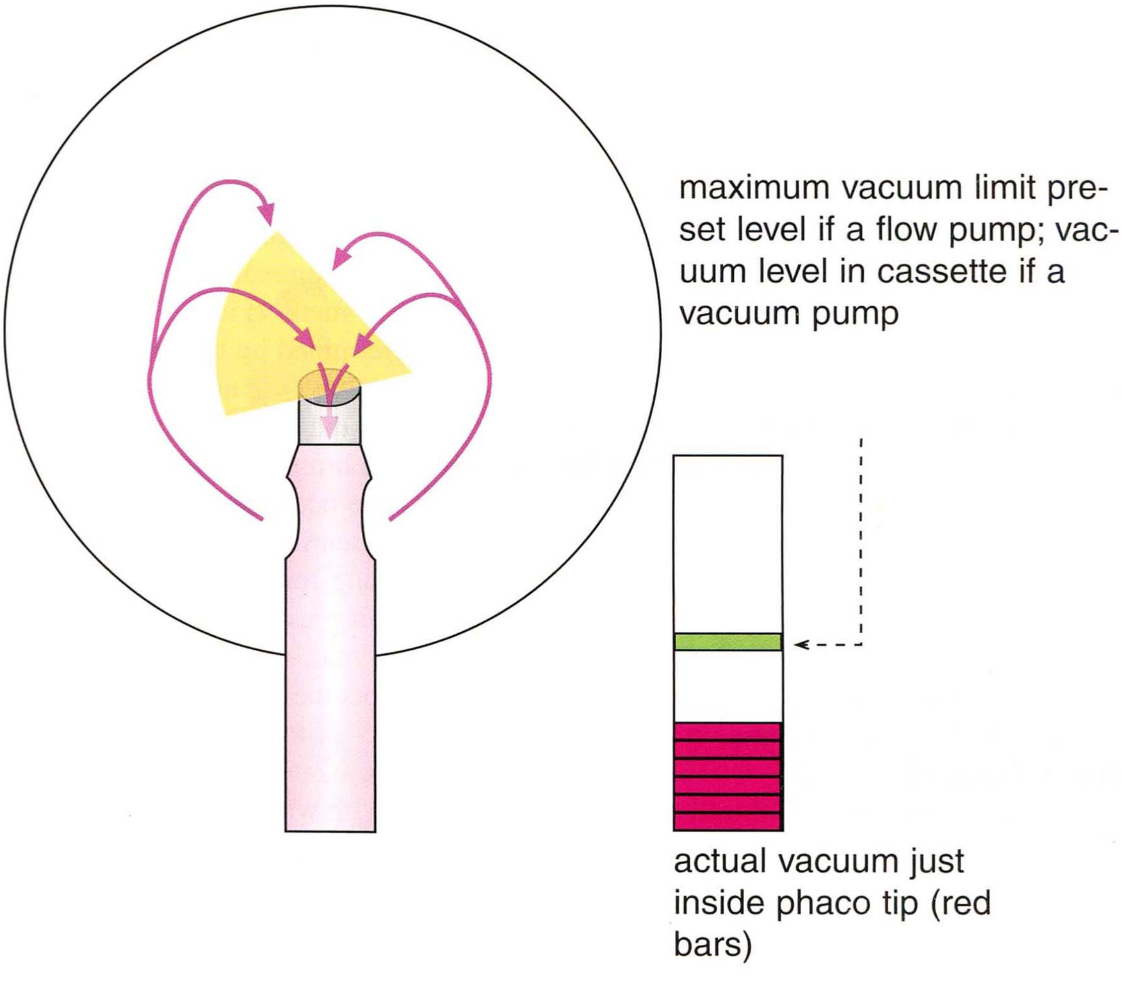

maximum vacuum limit pre-set level if a flow pump; vac-uum level in cassette if a vacuum pump
actual vacuum just inside phaco tip (red bars)

FIGURE 2-5

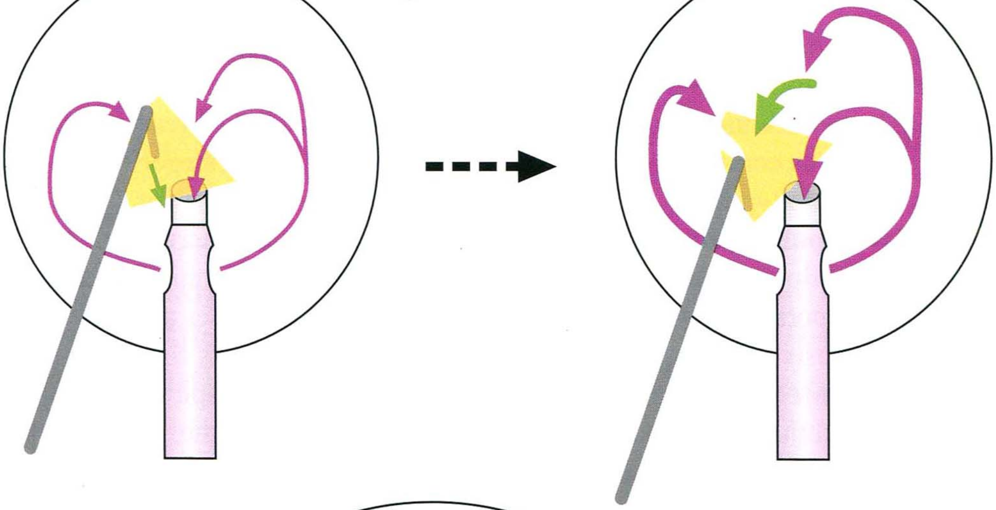
Flow and Vacuum Settings 3: Grip

The state of partial occlusion shown in Figure 2-5 might also be encountered by a surgeon who has engaged the fragment in order to manipulate it further (ie, to chop it into smaller pieces for easier carouseling). In this case, the pedal would be in position 2 after having used ultrasound only briefly to embed the tip, as opposed to the pedal position 3 that was used in Figure 2-5 for carouseling phacoaspiration of the fragment. However, because the tip is incompletely embedded with the aspiration port partially unoccluded, vacuum cannot build efficiently up to the preset vacuum limit. If the surgeon attempts to chop the fragment at this point and finds that the chopper dislodges the fragment from the tip prior to completing the chop (Figure 2-6-1), then it can be determined that insufficient holding force or grip is present. However, the solution in this case is not to increase the vacuum limit preset (with flow pumps) or the commanded vacuum (with vacuum pumps); this would serve only to raise the green bar on the meter (Figure 2-5) without changing the actual vacuum just inside the tip, a value that was determined by the degree of tip occlusion. The solution would be to completely embed the tip (Figure 2-6-2) so as to completely occlude the aspiration port, thus interrupting flow and transferring all of the pump's force into producing vacuum and holding power at the occluding fragment up to the limit established by the vacuum limit preset (see Figures 1-11 and 1-30). Note that with complete occlusion, the actual vacuum inside the phaco needle (red bars) has reached the green bar, representing the vacuum limit (flow pump) or commanded vacuum level (vacuum pump). If the holding force were still insufficient at this point, then it would be appropriate to raise the vacuum limit preset further. For more information on embedding the aspiration port to obtain a good vacuum seal, see Figures 3-30 through 3-32.

The complete occlusion of the aspiration port interrupts the fluidic circuit and stops intraocular flow; note the lack of purple flow arrows in Figure 2-6-2 (note absence of purple arrows relative to Figures 2-5 and 2-6-1). Therefore, adjusting the flow rate on a flow pump will not affect holding force in position 2; it will only change the speed with which the vacuum limit is reached (rise time) by changing the rotational speed of the pump head (see Figure 1-13). **In summation, <u>flow</u> is the relevant parameter when the aspiration port is unoccluded, while <u>vacuum</u> is the relevant parameter with complete tip occlusion; <u>both</u> parameters work together to enhance followability with partial tip occlusion**.

Figure 2-6 illustrates a dominant theme of Phacodynamics: **always optimize technique before turning to technology**. In this case, a higher and potentially more dangerous vacuum level (machine technology) was not needed to achieve clinically relevant grip. The surgeon only needed to optimize the technique by first completely embedding the phaco tip in order to achieve an efficient transfer of the machine's vacuum and gripping force.

Figure 2-6-1



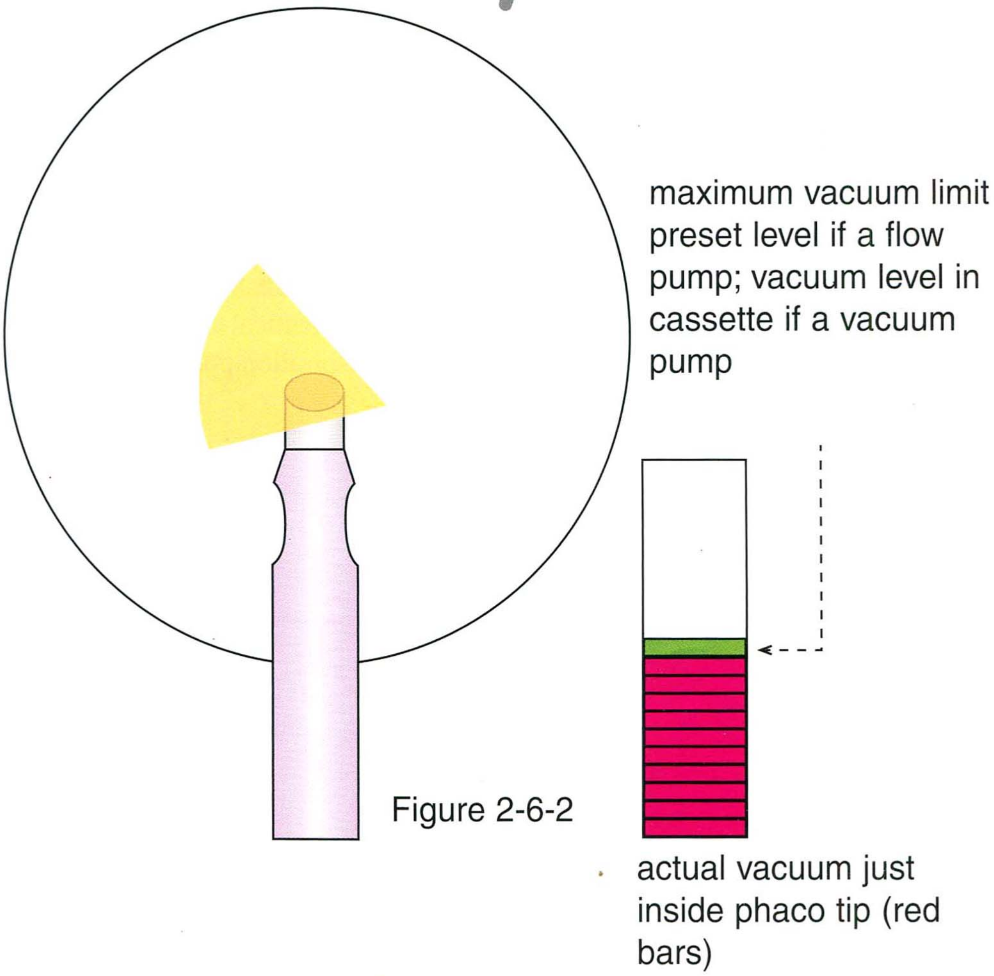


Figure 2-6-2

FIGURE 2-6

Control Inputs and Aspiration Port Occlusion: Flow Pumps vs Vacuum Pumps

In reviewing the logic of setting machine parameters, it is helpful to revisit the emphasis placed on constantly monitoring the aspiration port. As has been stressed throughout this book, the state of aspiration port occlusion is a critical determinant of the clinical reaction that is produced in response to various control inputs. Figure 2-7A summarizes and categorizes these variations for the two main pump types.

When using a **flow pump**, adjusting the commanded flow rate with an unoccluded aspiration port varies the actual flow rate and in turn proportionately affects the strength of attraction of material to the aspiration port. With an occluded aspiration port that precludes actual flow, adjusting the flow rate still adjusts the pump speed, which proportionately affects rise time. Adjusting the vacuum limit with an occluded aspiration port directly affects the aspiration line vacuum between the occlusion and the pump, and therefore proportionately affects the grip of the occluding fragment. With an unoccluded aspiration port, adjusting the vacuum limit does not typically have any clinical effect; however, the * in the chart refers to the exception discussed in the second paragraph with Figure 4-1.

When using a **vacuum pump**, the only fluidic parameter that the surgeon can adjust on the pump is commanded vacuum; these pumps do not have an independent flow rate control. However, as seen in Figure 1-28 and other examples, varying the commanded vacuum level proportionately controls the aspiration outflow rate when the aspiration port is not occluded, thereby affecting the strength and rate with which material is attracted to the aspiration port. When the aspiration port is occluded, varying the commanded vacuum level proportionately controls the grip with which the occluding fragment is held; note the identical clinical effect of controlling grip by varying the vacuum limit with a flow pump and an aspiration port occlusion as described in the preceding paragraph.

parameter	aspiration port occlusion	effect
commanded flow rate (cc/min)	no	attracts material to aspiration port
	yes	rise time
vacuum limit (mm Hg)	no	none*
	yes	grips material at aspiration port
flow pump		

parameter	aspiration port occlusion	effect
commanded vacuum (mm Hg)	no	controls flow rate; attracts material to aspiration port
	yes	grips material at aspiration port
vacuum pump		

FIGURE 2-7A

Control Inputs and Aspiration Port Occlusion: Flow Pumps vs Vacuum Pumps

In reviewing the logic of setting machine parameters, it is helpful to revisit the emphasis placed on constantly monitoring the aspiration port. As has been stressed throughout this book, the state of aspiration port occlusion is a critical determinant of the clinical reaction that is produced in response to various control inputs. Figure 2-7A summarizes and categorizes these variations for the two main pump types.

When using a **flow pump**, adjusting the commanded flow rate with an unoccluded aspiration port varies the actual flow rate and in turn proportionately affects the strength of attraction of material to the aspiration port. With an occluded aspiration port that precludes actual flow, adjusting the flow rate still adjusts the pump speed, which proportionately affects rise time. Adjusting the vacuum limit with an occluded aspiration port directly affects the aspiration line vacuum between the occlusion and the pump, and therefore proportionately affects the grip of the occluding fragment. With an unoccluded aspiration port, adjusting the vacuum limit does not typically have any clinical effect; however, the * in the chart refers to the exception discussed in the second paragraph with Figure 4-1.

When using a **vacuum pump**, the only fluidic parameter that the surgeon can adjust on the pump is commanded vacuum; these pumps do not have an independent flow rate control. However, as seen in Figure 1-28 and other examples, varying the commanded vacuum level proportionately controls the aspiration outflow rate when the aspiration port is not occluded, thereby affecting the strength and rate with which material is attracted to the aspiration port. When the aspiration port is occluded, varying the commanded vacuum level proportionately controls the grip with which the occluding fragment is held; note the identical clinical effect of controlling grip by varying the vacuum limit with a flow pump and an aspiration port occlusion as described in the preceding paragraph.

parameter	aspiration port occlusion	effect
commanded flow rate (cc/min)	no	attracts material to aspiration port
	yes	rise time
vacuum limit (mm Hg)	no	none*
	yes	grips material at aspiration port
flow pump		

commanded vacuum (mm Hg)	no	controls flow rate; attracts material to aspiration port
	yes	grips material at aspiration port
vacuum pump		

FIGURE 2-7A

Parameter Modulation with Hardware Modification

New technology will always be introduced that may enhance surgical safety or performance or both. However, these new devices may affect machine parameters, and the surgeon should anticipate these changes based on the design of the new device. For example, Alcon offers the Aspiration Bypass System phaco needle (Figure 1-63A), which incorporates a small opening that allows some flow even with complete occlusion of the distal aspiration port. This design offers potential benefits for both tip cooling and surge control. However, a surgeon who tries the tip for the first time should anticipate that his or her typical fluidic settings will need to be modified based on the ABS port, which in effect creates an incomplete vacuum seal even with complete occlusion of the aspiration port. Figure 2-7B-1 is a reiteration of Figure 2-6, illustrating how actual vacuum inside of the phaco needle reaches the preset vacuum limit with complete occlusion of a standard 19 Ga. needle. Figure 2-7B-2 shows that even when the distal aspiration port is completely occluded on an ABS tip (left diagram), the ABS port still allows some flow that is analogous to an incomplete occlusion of a standard needle (right diagram, which is the same as Figure 2-5).

In order to compensate for the corresponding decrease in grip, flow rate (on a flow pump) should be increased approximately 15 to 20% over the surgeon's standard setting for a non-ABS needle of the same gauge; the vacuum limit may have to be raised slightly as well. The faster flow rate will cause the vacuum to come much closer to the preset vacuum limit because of the high fluidic resistance of the small ABS port (see Figure 2-7B-3). A vacuum pump surgeon must increase commanded vacuum by approximately 15 to 20% so that the increased induced flow will have the same effect as just described for a flow pump. Without the anticipation of these parameter modifications, a surgeon using his or her standard settings might come to an inappropriate conclusion that the ABS design had inferior holding force relative to a standard tip, whereas the ABS tip simply needs appropriate phacodynamic modification of machine parameters to effectively exploit its benefits while delivering the expected performance of nuclear gripping.

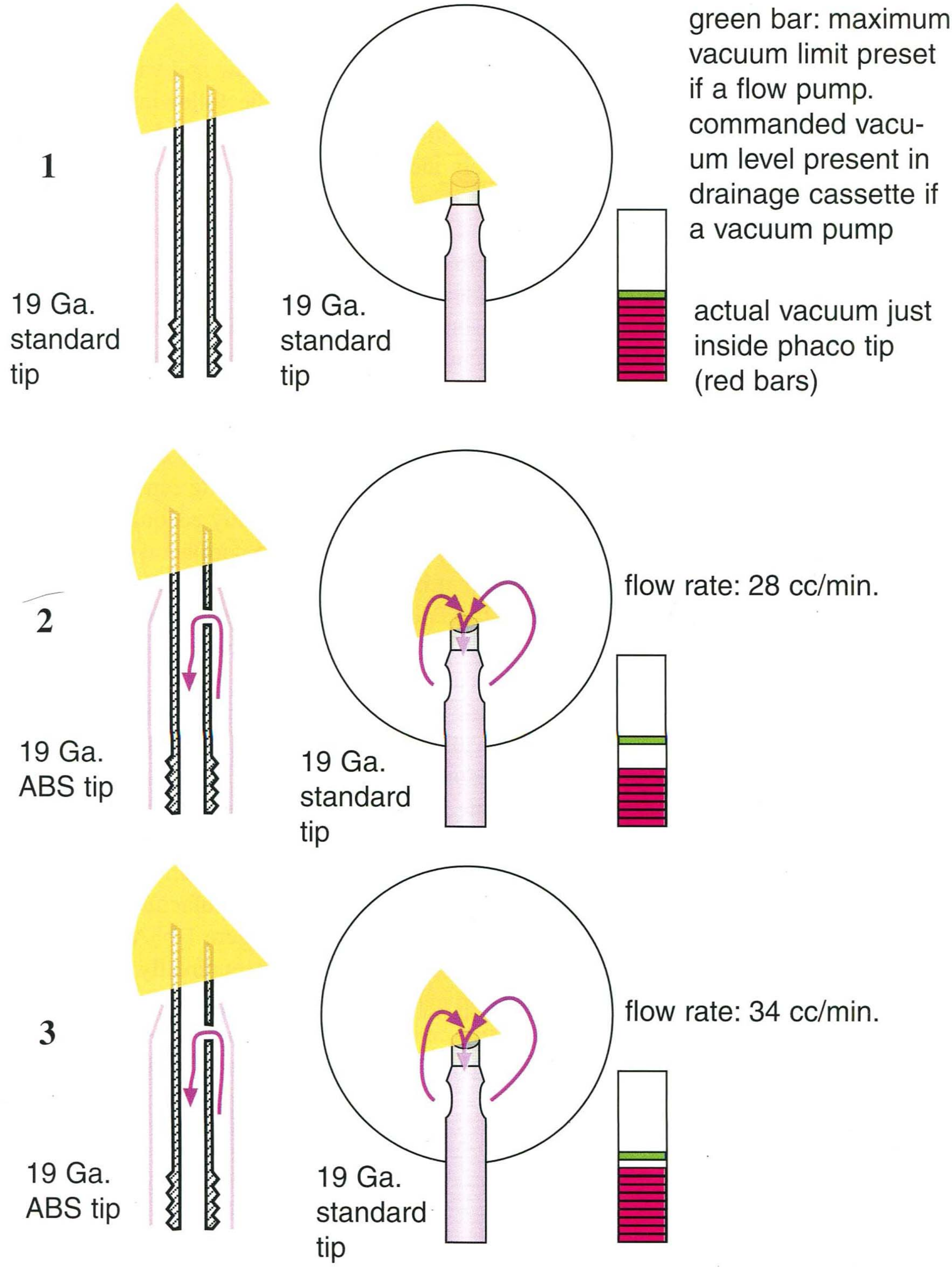

1
19 Ga.
standard
tip
19 Ga.
standard
tip
green bar: maximum vacuum limit preset if a flow pump. commanded vacuum level present in drainage cassette if a vacuum pump
actual vacuum just inside phaco tip (red bars)
2
19 Ga.
ABS tip
19 Ga.
standard
tip
flow rate: 28 cc/min.
3
19 Ga.
ABS tip
19 Ga.
standard
tip
flow rate: 34 cc/min.

FIGURE 2-7B

Sculpting Settings: Vacuum, Flow, and Bottle Height

Whereas Figures 2-4 through 2-7 established the relevancy of flow and vacuum parameter adjustment according to the amount of aspiration port occlusion, the following diagrams will examine the logic behind setting these parameters with regard to their function during specific surgical techniques. Although sculpting is a relatively inefficient mode of phacoemulsification (see Figure 1-50), it can nonetheless be a useful prelude in preparing the nucleus for various segmentation methods including cracking and chopping. Figure 2-8 illustrates the sculpting of a central groove in preparation for cracking the cataract into two heminuclei. **High vacuum** is **not needed** at this stage because there are not yet any large fragments which need to be occluded and gripped, and the particulate emulsate produced by ultrasonic tip action does not typically provide any appreciable resistance which would need high vacuum to overcome. Indeed, even with a high vacuum limit preset, actual vacuum would not necessarily reach the preset level because the tip is usually not occluded more than halfway during sculpting (see Figures 1-50 and 2-5). Furthermore, high vacuum is not needed to counteract the repulsive action of ultrasound since the nucleus is held stationary by its intact structure at this point along with the surrounding capsule and zonules. Therefore, **low vacuum settings** of approximately 60 mm Hg are usually adequate for sculpting while still providing a reasonable safety margin in case of inadvertent peripheral epinuclear, capsular, or iris incarceration. Levels lower than 30 mm Hg increase the likelihood of aspiration line clogging when sculpting a dense nucleus which produces larger particles when emulsified; this potential problem of course varies according to the particular machine being used, especially with regard to the inner diameter of the aspiration line and the phaco needle.

Flow rates can be relatively **low** for sculpting since the only surgical function of flow at this stage is to remove the emulsified lens material without allowing it to fill the anterior chamber. If lens particles are observed in the anterior chamber and the aspiration port appears unoccluded, you should assume the handpiece and/or aspiration line is clogged and take appropriate steps (remove the tip from the eye, inspect the aspiration line for kinks, increase vacuum with a test chamber to reestablish flow as observed in the bottle drip chamber, etc). Again, with a well-designed machine that guards against clogging, you can use the lowest flow rate the manufacturer recommends; recall that a minimum flow is required for ultrasonic tip cooling (see Figure 1-63A). A typical low flow range is around 20 cc/min. Recall that this flow rate can be either set directly on a flow pump machine or achieved indirectly on a vacuum pump machine by an appropriate commanded vacuum level with the partially occluded sculpting tip (see discussion with Figure 1-40A). With a low flow rate, the **bottle height** can be correspondingly moderate (eg, 70 cm) and still produce a stable and deep anterior chamber.

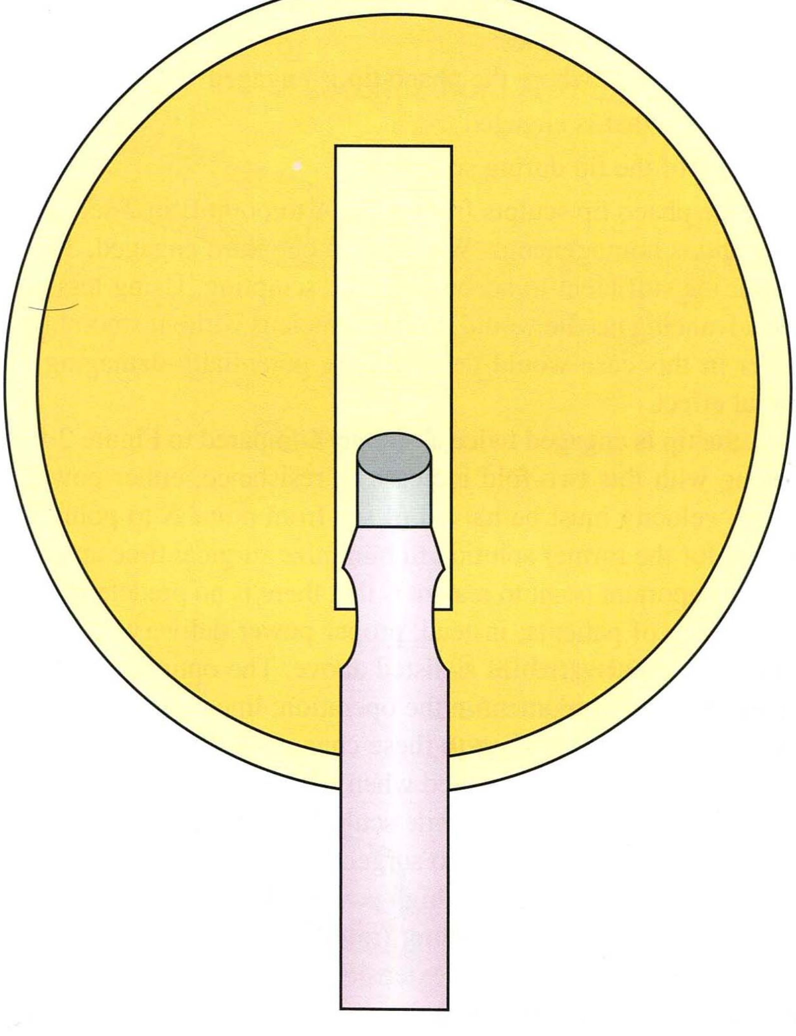


FIGURE 2-8

Sculpting Settings: Ultrasound

The parameter of ultrasound power during sculpting is set to achieve smooth sculpting without pushing the nucleus (too little power) or delivering excessive intraocular energy with increased potential for complications, such as a wound burn or suddenly piercing the nucleus and possibly the capsule (too much power). The appropriate phaco power for a given surgical case is determined intraoperatively by three variables:

1. The density of the nucleus where the phaco tip is engaged
2. The amount of the tip that is engaged
3. The linear velocity of the tip during sculpting

In Figure 2-9-2, the phaco tip sculpts from point A to point B in 2 sec (linear velocity). The nuclear density is 2+ and is homogeneous. With the tip one third engaged, 30% phaco power (on this particular machine) is sufficient to accomplish the sculpting. Using less power would cause zonular stress as the advancing needle would push the nucleus without smoothly sculpting through it. Using more power in this case would deliver more potentially damaging intraocular energy without any beneficial effect.

In Figure 2-9-1, the tip is engaged twice as deeply compared to Figure 2-9-2. In order to preserve smooth sculpting with this two-fold increase in resistance, either power must be doubled (60%) or the linear tip velocity must be halved (4 sec from point A to point B). A more experienced surgeon may opt for the former solution to minimize surgical time and amount of intraocular irrigating fluid. The important point to realize is that there is no predetermined "correct" power setting for a given category of patients; instead, proper power delivery is determined intraoperatively and is dependent on other variables as listed above. The optimum power changes as these variables change from moment to moment in the operation; linear phaco power control is invaluable in making smooth transitions to adapt to these changes. I often use a high maximum phaco power preset (70%) and titrate power as needed when sculpting with linear pedal control, increasing power if nuclear displacement is noted while sculpting.

A common error for the beginning phaco surgeon is to use far too little power, the rationale being that less power is inherently safer than high power. However, as explained above, too little power can lead to numerous pitfalls by pushing (rather than carving through) the nucleus with potential zonular stress/disruption as well as extension of any preexisting tears in the capsulotomy. **The safest phaco is performed not with low power but rather with appropriate power** for the variables as listed above. Your microscopic view should be of the phaco needle smoothly carving through a relatively immobile nucleus; if the nucleus is moving significantly, you must increase power, decrease the linear velocity of sculpting, or decrease the amount of the tip engaged. Also, remember that **ultrasound energy should be engaged only on each forward sculpting stroke**; the pedal should be raised to position 2 or 1 to disengage ultrasound on each backstroke. Otherwise, twice as much ultrasound energy would be expended in the anterior chamber than is necessary.

Notwithstanding the foregoing description of the need for more ultrasound power with increasing partial tip engagement, recall that power requirements will decrease once the tip becomes fully occluded and vacuum augments ultrasound in aspirating nuclear material (see Figure 1-50).

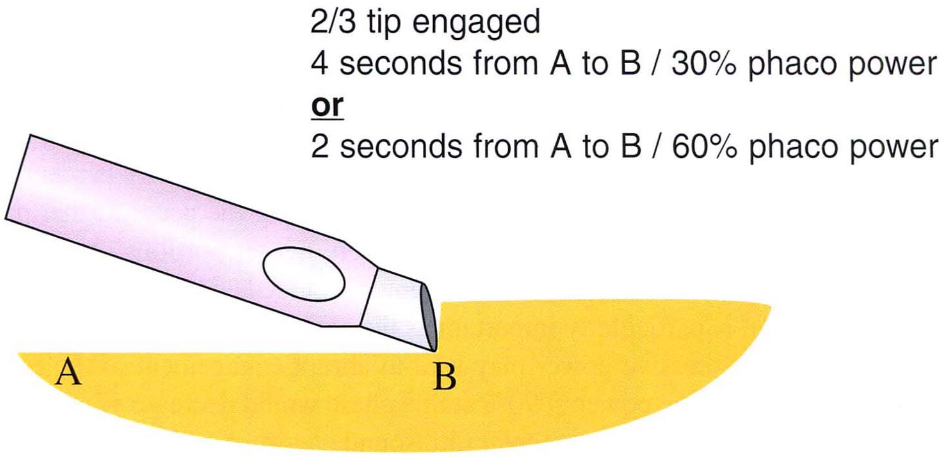


Figure 2-9-1

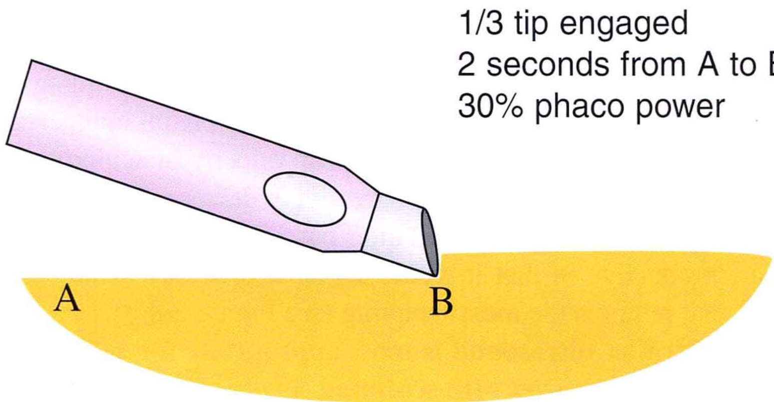


Figure 2-9-2

FIGURE 2-9

Linear Phaco Sculpting

Figure 2-9 utilized a homogeneous nuclear density to illustrate various concepts. However, most nuclei have variable density with the central portion being most dense. Some nuclei have a smooth transition of density, while others have a more abrupt "lens within a lens" configuration which is readily apparent on preoperative slit-lamp examination. If the amount of tip engaged and the linear velocity of sculpting remain constant, the phaco power must be varied while sculpting through these nuclei with variable density. The following illustrations (Figure 2-10) assume a very dense central nucleus and a maximum phaco power preset of 100%. Thirty percent linear power may be sufficient to begin sculpting in the periphery. Depressing the pedal further provides 60% and then 90% as sculpting proceeds through progressively denser portions of the nucleus. Note that the pedal is let up to decrease the power as the center is passed and less dense material is again encountered; this concept is particularly important as the sculpting tip approaches the contra-incisional epinucleus, where excessive power may lead to abrupt engagement of the epinucleus and juxtaposed capsule. Keeping the power at 90% at this phase would decrease your safety margin as well as needlessly deliver excessive intraocular ultrasound energy. Another important rule for limiting intraocular ultrasound (as mentioned with Figure 2-9) is remembering to relax the foot pedal into position 2 or 1 when retracting the phaco tip to prepare another sculpting excursion.

Note that the above scenario describes how to vary power while maintaining a constant degree of tip engagement and linear velocity of sculpting. However, the principles from Figure 2-9 could also be applied to vary different parameters in Figure 2-10. For example, ultrasound power and the degree of tip engagement could be held constant while the linear velocity of sculpting is progressively slowed as the central densest nucleus is approached and then progressively accelerated as it is passed. However, safety might be compromised as the more vulnerable peripheral nucleus and capsule are approached at an accelerating linear velocity of sculpting, which would allow less time for the surgeon to react in case of inadvertent peripheral epinuclear or capsular incarceration. Alternatively, the ultrasound power and linear velocity of sculpting could be held constant while the degree of tip engagement was progressively decreased when approaching the central densest nucleus and progressively increased after passing through it. However, this latter solution would be counterproductive in that it would sculpt less deeply in the central nucleus, which is the thickest area that requires the most sculpting (see Figure 3-4-3).

Linear continuous control of ultrasound is most appropriate for sculpting; recall that Pulse or Burst Modes should not be used with sculpting (Figure 1-58).

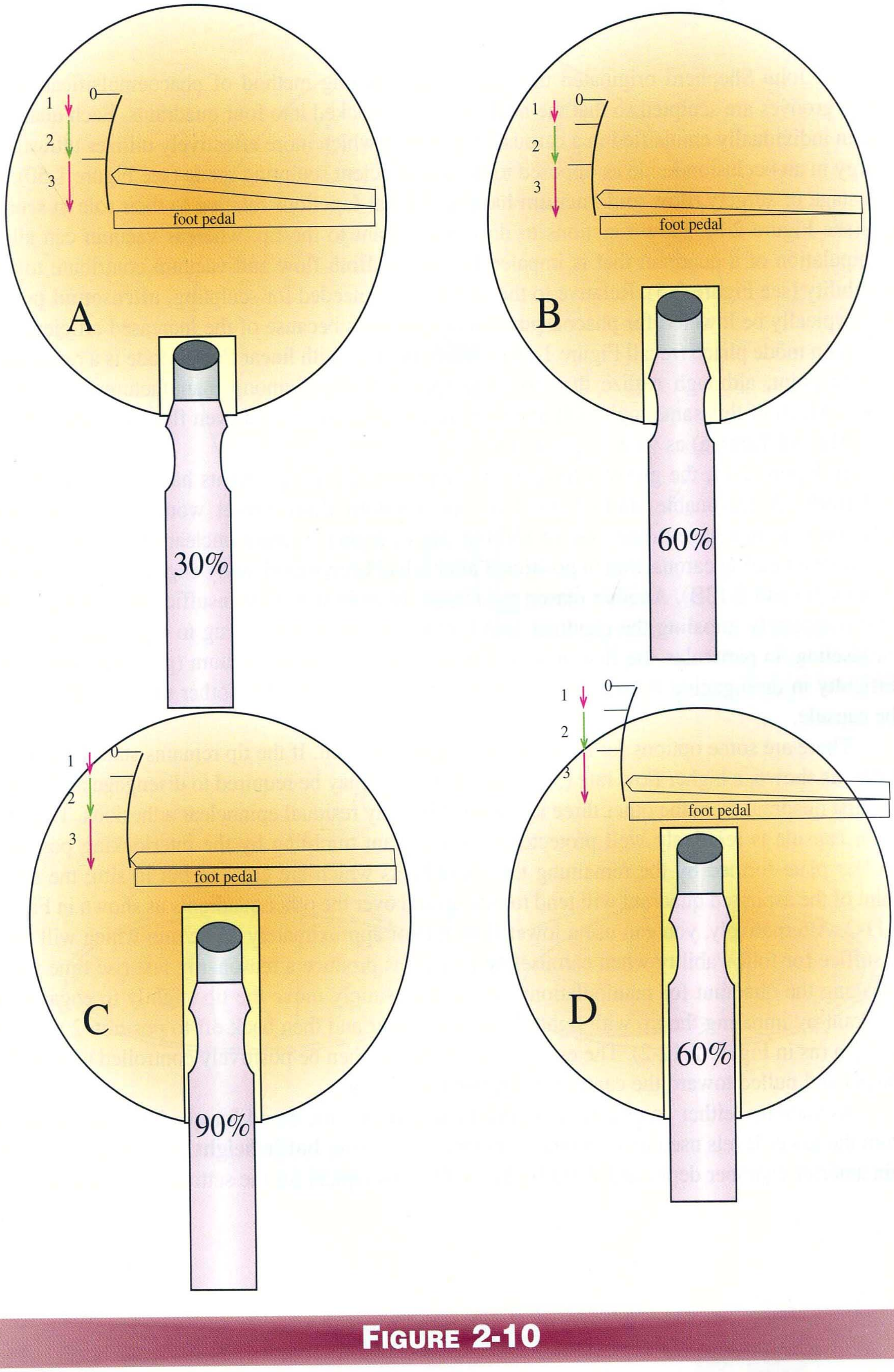

0
1
2
3
foot pedal
A
30%
0
1
2
3
foot pedal
B
60%
0
1
2
3
foot pedal
C
90%
0
1
2
3
foot pedal
D
60%

FIGURE 2-10

Quadrant Settings 1

Dr. John Shepherd originated the popular quadranting method of phacoemulsification, in which grooves are sculpted so that the nucleus can be cracked into four quadrants. Each quadrant is then individually emulsified in a carouseling fashion which more effectively utilizes ultrasound energy in an occlusion mode as opposed to the less efficient sculpting mode (see Figure 1-50). At this stage of surgery, **flow and vacuum** have additional functions relative to their role in sculpting (see Figure 2-8). Flow functions to draw a quadrant to the tip, whereas vacuum can allow manipulation of a quadrant that is impaled by the tip. Both flow and vacuum contribute to followability (see Figure 2-5). Relative to the higher levels needed for sculpting, **ultrasound power** may typically be lowered for phacoaspiration of quadrants because of the increased efficiency of occlusion mode phaco (recall Figure 1-50); 40% maximum with linear Pulse Mode is a reasonable starting point, although realize that no standardization exists among manufacturers for phaco power. Much of this same logic will apply to chopped fragments and even flipped nuclei (Phaco Flip, Tilt and Tumble) as well as quadrants.

In Figure 2-11, the grooves have been completed and the quadrants have all been cracked posteriorly. A reasonable starting point for the **vacuum limit preset** would be 80 mm Hg, although you may have to increase to 150 mm Hg or higher if dense nuclear chatter disengages the quadrant during carouseling in position 3 after it had been significantly engaged by the tip (see Figures 2-5 and 2-13B). Another reason to increase vacuum would be insufficient holding power after completely impaling the quadrant (see Figure 2-6) when attempting to pull it centrally for carouseling; in particular, the first quadrant often requires a higher vacuum (grip) because of the difficulty in disengaging it from its interlocked position caused by the other three quadrants and the capsule.

There are some options for **flow rate** setting at this point. If the tip remains stationary in the center as shown, a higher flow rate (35 cc/min or higher) may be required to disengage and attract the first quadrant from the other three as well as from any residual epinuclear adhesions. The posterior capsule is relatively well protected from quadrant tumbling by the interlocking posterior nuclear plate formed by the remaining three quadrants which are cracked but in situ; the sharp point of the aspirated quadrant will tend to ride up and over the other quadrants as shown in Figure 2-11-2. Alternatively, you can use a lower flow rate of approximately 25 cc/min which will likely suffice for followability when carouseling as well as produce a reasonably fast rise time when engaging the quadrant for manipulation; in this case, simply move the tip slightly to engage the quadrant by impaling the tip with light ultrasound power and then back off to position 2 to build vacuum (as in Figure 2-12-2). The engaged quadrant can then be positively controlled as it is dislodged and pulled toward the center for safer emulsification.

As vacuum (either commanded or limit) and flow are increased for quadrant manipulation from the lower levels used in sculpting, remember to increase **bottle height** accordingly to maintain anterior chamber depth and stability; 80 to 90 cm is typical for the settings discussed above.

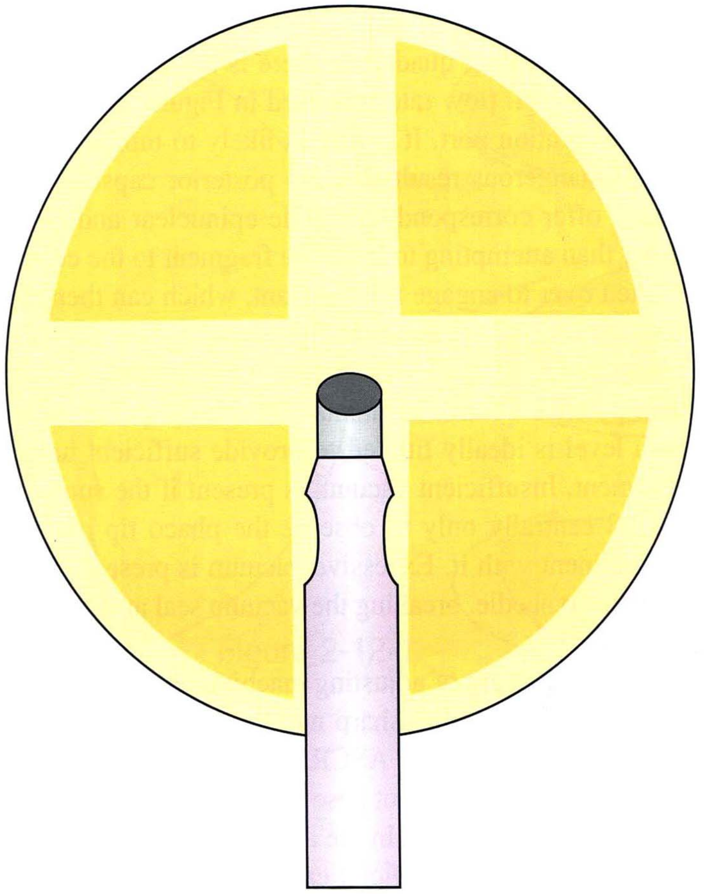


Figure 2-11-1
(top view)

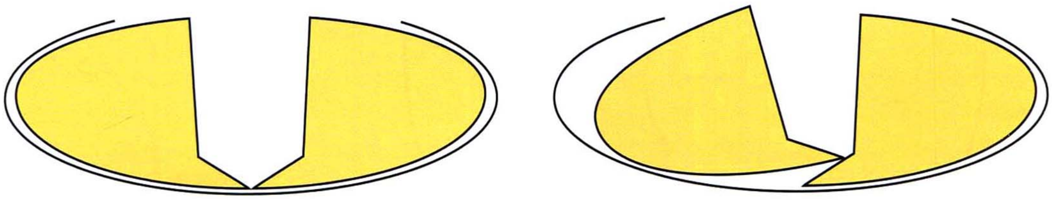


Figure 2-11-2
(side view)

FIGURE 2-11

Quadrant Settings 2

With only one or two remaining quadrants, there is not as much latitude with flow rate as there was in Figure 2-11. If a high flow rate was used in Figure 2-12-1, the quadrant is likely to tumble on its way to the aspiration port. It is just as likely to tumble its sharp tip posteriorly as anteriorly with potentially dangerous results for the posterior capsule, especially when dealing with hard cataracts which offer correspondingly little epinuclear and cortical protection for the capsule. Therefore, rather than attempting to draw the fragment to the centrally placed phaco needle, the phaco tip is moved over to engage the quadrant, which can then be drawn under vacuum grip to the center of the pupil for safer carouseling phacoaspiration. By using a low flow rate and positively engaging the quadrant (first with light ultrasound and then with pump vacuum only) as shown in Figure 2-12-2, positive control is maintained and the potential for random tumbling is minimized. The vacuum level is ideally titrated to provide sufficient holding force to positively control the engaged fragment. Insufficient vacuum is present if the surgeon attempts to draw the fragment in Figure 2-12-2 centrally only to observe the phaco tip pulling out of the fragment instead of drawing the fragment with it. Excessive vacuum is present if abrupt aspiration occurs just around the tip of the phaco needle, breaking the vacuum seal and causing loss of grip and control (see Figure 3-31).

With regard to the above concept of adjusting machine parameters and surgical technique in order to protect the posterior capsule from sharp nuclear edges, I must acknowledge Dr. Robert Osher's award-winning video from the 1997 ASCRS Film Festival. This video innovatively illustrated that sharp nuclear edges probably do not pose a threat to the posterior capsule. Nevertheless, the preceding paragraph is a useful exercise in the application of phacodynamic principles, and it may in fact be useful when dealing with difficult cases such as positive vitreous pressure or possibly abnormal posterior capsules (eg, posterior polar cataracts, pseudoexfoliation syndrome, small posterior capsular tear).

Although continuous linear ultrasound may be used for carouseling phacoaspiration of nuclear fragments, power modulations such as Pulse and HyperPulse are more efficient and should be utilized when available (Figure 1-57).

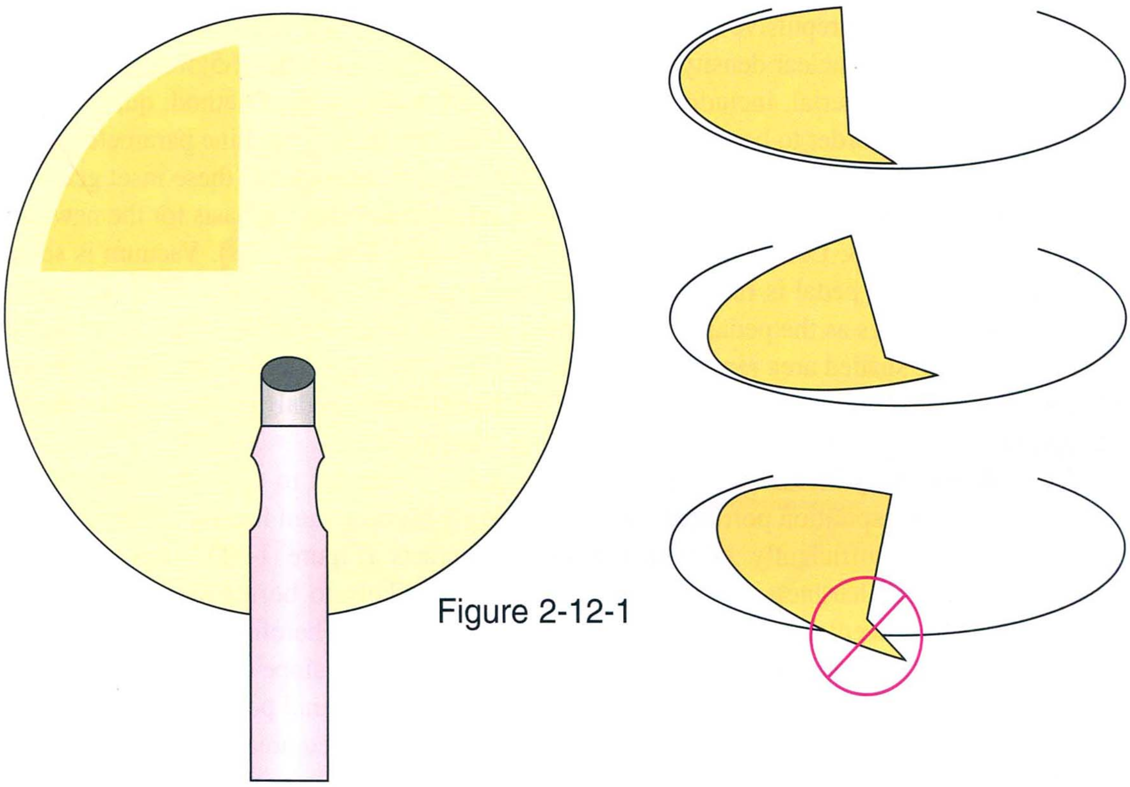


Figure 2-12-1

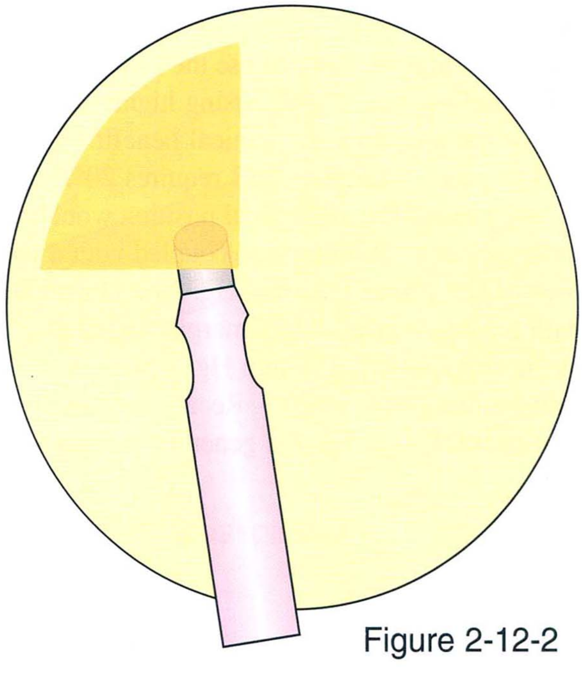


Figure 2-12-2

FIGURE 2-12

Settings for Quadrant/Fragment Emulsification: Balancing Fluidics and Ultrasound

Ultrasound power (repulsive) is titrated along with fluidic parameters (flow and vacuum, which are attractive) to nuclear density as discussed with Figures 1-51 and 2-5; this applies to any free-floating nuclear material, including whole nuclei with a Phaco Flip Method, quadrants, and chopped fragments. In order to better visualize the relationship among machine parameters during this stage, Figure 2-13 includes a graph that represents a Dual Linear Pedal (these inset graphs are patterned after illustrations from Dr. Paul Koch). This graph also forms the basis for the new video overlay on the Bausch & Lomb Millennium (see Figures 2-16A and 2-16B). Vacuum is seen to linearly increase as the pedal is further depressed in pitch from its top position of 0, while ultrasound linearly increases as the pedal is moved in a yaw (lateral) direction from its center position of 0. The light blue shaded area represents an appropriate range of optimal positions for the pedal for a given nuclear density and a given machine. In other words, pedal position within the blue area represents an appropriate balance of fluidics and ultrasound.

As nuclear density increases, more ultrasound power is needed to trim the fragment sufficiently to fit into the aspiration port because even relatively high vacuum levels cannot deform the crystalline structure sufficiently as with the softer cataracts (Figure 1-51). However, as the cataract's density and hardness become greater, it is more likely to be repelled by the axially vibrating ultrasonic needle, especially at higher power settings. Therefore, **increasing power requires a proportional increase in vacuum and/or flow**; note the slope of the blue shaded area in Figure 2-13, which represents acceptable combinations of ultrasound power and vacuum level for this particular machine. Any pedal position within this blue shaded area will result in this particular fragment progressively aspirating into the phaco needle in a carouseling fashion as indicated by the curved arrow.

Naturally, the surgeon wants to use the lowest level of combined parameters that will suffice for a given level of nuclear density; using higher levels (lower on the blue slope) decreases the safety margin without adding any clinical benefit. For example, let us stipulate that the nuclear density of the fragment in Figure 2-13 requires 20% ultrasound power for sufficient emulsification to allow aspiration. The ideal pedal position would be that represented by the gray bar, which uses this minimum level of ultrasound coupled with a vacuum of 120 mm Hg. If the pedal is put in the position of the red bar (180 mm Hg, 20% ultrasound power), the fragment will still be aspirated but with a compromised safety margin due to the higher than necessary vacuum relative to the gray bar; in other words, 180 mm Hg is 50% more than the 120 mm Hg that is sufficient to balance an ultrasound power of 20%. Recall that these numbers are representative of this particular schematic machine, although the general concepts apply to all machines.

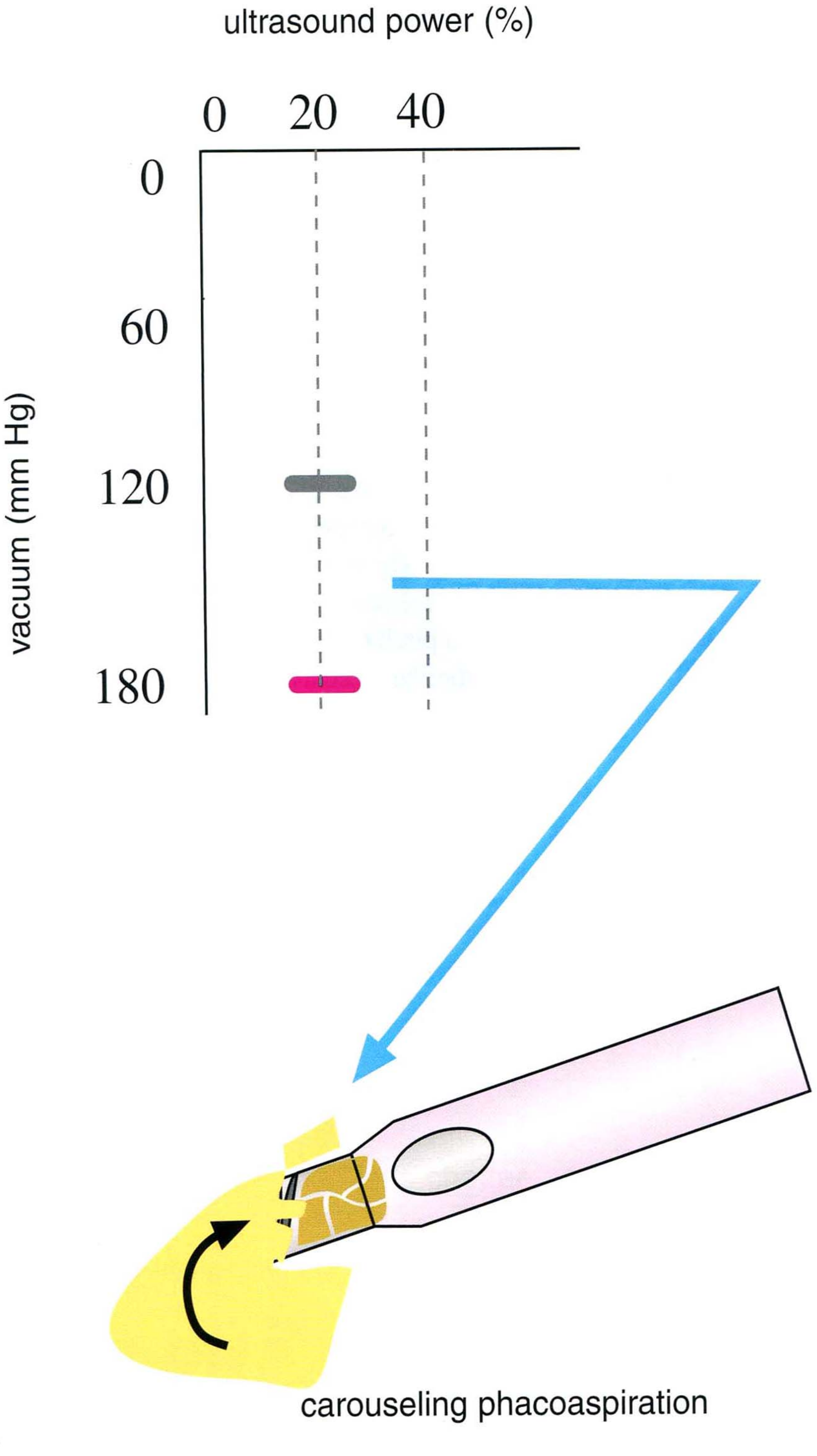

ultrasound power (%)
0
20
40
0
60
120
180
vacuum (mm Hg)
carouseling phacoaspiration

FIGURE 2-13A

Settings for Quadrant/Fragment Emulsification: Balancing Fluidics and Ultrasound (continued)

Although the blue bar (Figure 2-13B) is within the light blue shaded area (therefore an acceptable balance of ultrasonic repulsion and fluidic attraction), it would represent an inappropriately high combination of parameters (40% ultrasound power and 180 mm Hg vacuum) for this nuclear fragment, which can be more safely phaco-aspirated with the lower parameters present at the gray bar's position (Figure 2-13A). A pedal at the purple bar's position (0% ultrasound, 180 mm Hg vacuum, Figure 2-13B) will cause the nuclear fragment to be gripped but not aspirated because it has less than the minimum amount of ultrasound (20%) that is required for emulsification of this particular nuclear density. However, this would be an appropriate position to grip and manipulate the fragment (eg, for centralization or further chopping) once the aspiration port had been appropriately embedded with light ultrasound power.

If the pedal is placed in the position of the green bar (120 mm Hg, 40% ultrasound power, Figure 2-13B), the ultrasound power will be too great for the amount of vacuum; the fragment will not be aspirated but will instead chatter against the tip as it rapidly alternates between repulsion from ultrasound and attraction by vacuum/flow. If the surgeon wishes to maintain 40% ultrasound power, then the pedal must be depressed further in pitch until it is within the blue shaded area (blue bar) so that attractive fluidic forces will overcome the repulsive ultrasonic forces so that the fragment can be effectively aspirated. As discussed above, however, this would represent an inappropriately excessive use of parameters because a lesser combination (gray bar in Figure 2-13A) would suffice for the nuclear density of this particular fragment.

Figures 2-13A and 2-13B have discussed the concepts of balancing ultrasound and fluidics, as well as the logic of setting parameters according to nuclear density. Although a Dual Linear Pedal was used in the diagrams, these concepts are valid for any machine.

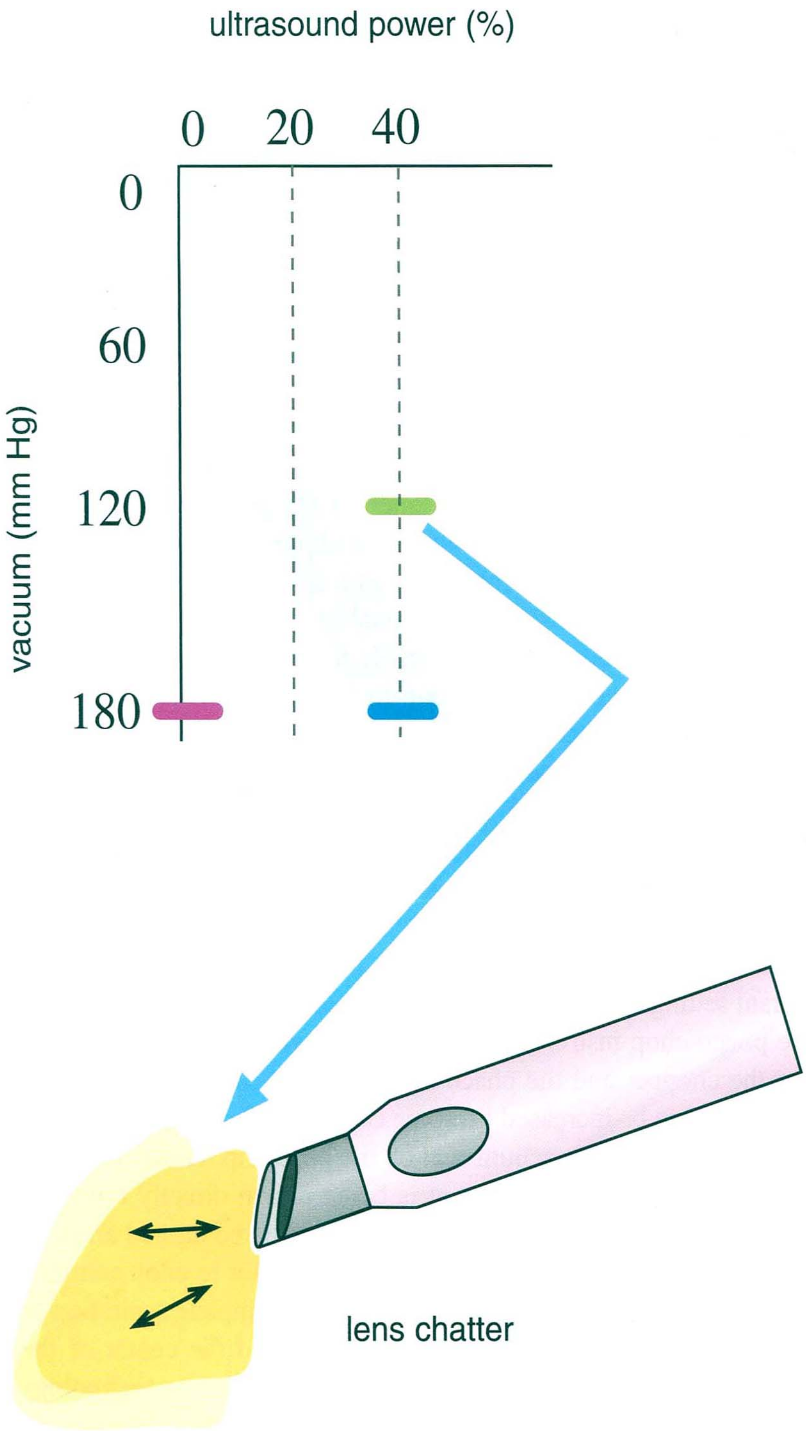

ultrasound power (%)
0
20
40
0
60
120
180
vacuum (mm Hg)
lens chatter

FIGURE 2-13B

Phaco Chop Settings: Horizontal Chop

The original phaco chop method, invented by Dr. Kunihiro Nagahara, involves impaling the nucleus with the phaco tip either as a first step or, as shown in Figure 2-14, after first sculpting a small bowl to allow access to the denser central nucleus which will give the best vacuum seal. Then, after allowing for rise time to build vacuum to the panel preset level, the phaco chop instrument (inserted through the side-port incision) is embedded in the nucleus at the periphery and drawn **horizontally** toward the phaco tip, splitting the nucleus as it advances (green and blue arrows). The nucleus is then rotated and the process is repeated to produce multiple nuclear fragments which are then safely emulsified in the center of the posterior chamber or iris plane. Because the aspiration port is completely occluded during chopping, **flow rate** is not an important parameter other than its effect on rise time. If a flow pump is used, 30 cc/min is a useful compromise between a reasonably rapid rise time and a reasonably stable anterior chamber. If a vacuum pump is used at a typical vacuum setting of 240 mm Hg that may be required for sufficient grip, anterior chamber stability can be compromised due to the correspondingly rapid induced flow when the aspiration port is not occluded. When the chop is completed and the occlusion breaks, the subsequent induced flow with a standard needle would be over 60 cc/min. However, a MicroFlow, Flare Tip, or similar needle with a reduced inner diameter (therefore increased fluidic resistance) significantly reduces this flow to a safer level (see Figure 1-40A). Additionally, the surgical technique should be optimized to use the high vacuum level during the actual manipulation and chop when gripping the nucleus, and then to dynamically decrease the vacuum with linear pedal control just as the chop is completed to minimize the surge potential (Figure 2-16B).

The most important setting for chopping is **vacuum**, which needs to be sufficient to stabilize the nucleus while the phaco chop instrument is splitting it, even though the nucleus is mechanically fixated between the chopper and the phaco tip. For many cases, 120 mm Hg may be adequate, but this level may need to be increased (in some cases to 240 mm Hg or higher) if the action of the phaco chopper is dislodging the vacuum seal on the phaco tip. However, before raising the vacuum level, make sure the chopping instrument is being drawn directly toward the phaco tip (green arrow). If it is being drawn at a slightly different vector (ie, red dashed arrow), a torque will be induced which can dislodge the nucleus from the phaco tip prior to chop completion (see also Figure 2-6-1, which illustrates this phenomenon secondary to incomplete aspiration port occlusion as well as a chopper movement that is not quite directly toward the center of the phaco tip). Therefore, make sure to **optimize surgical technique before turning to technology** and unnecessarily raising vacuum and thereby lowering your safety margin. It should be noted that once the chopper is drawn almost completely up to the phaco tip, an alternate vector (red solid arrow) may then intentionally be used to further extend the nuclear crack. Some surgeons actually prefer this method because the chop fracture is less likely to enter the aspiration port and break the vacuum seal and grip. However, if this technique is employed, then vacuum will likely need to be raised accordingly to maintain a firm hold on the nucleus by the phaco tip as discussed above. When using higher vacuum levels, remember to raise **bottle height** accordingly to prevent postocclusion surge (typically 95 to 110 cm with vacuum levels between 200 and 250 mm Hg).

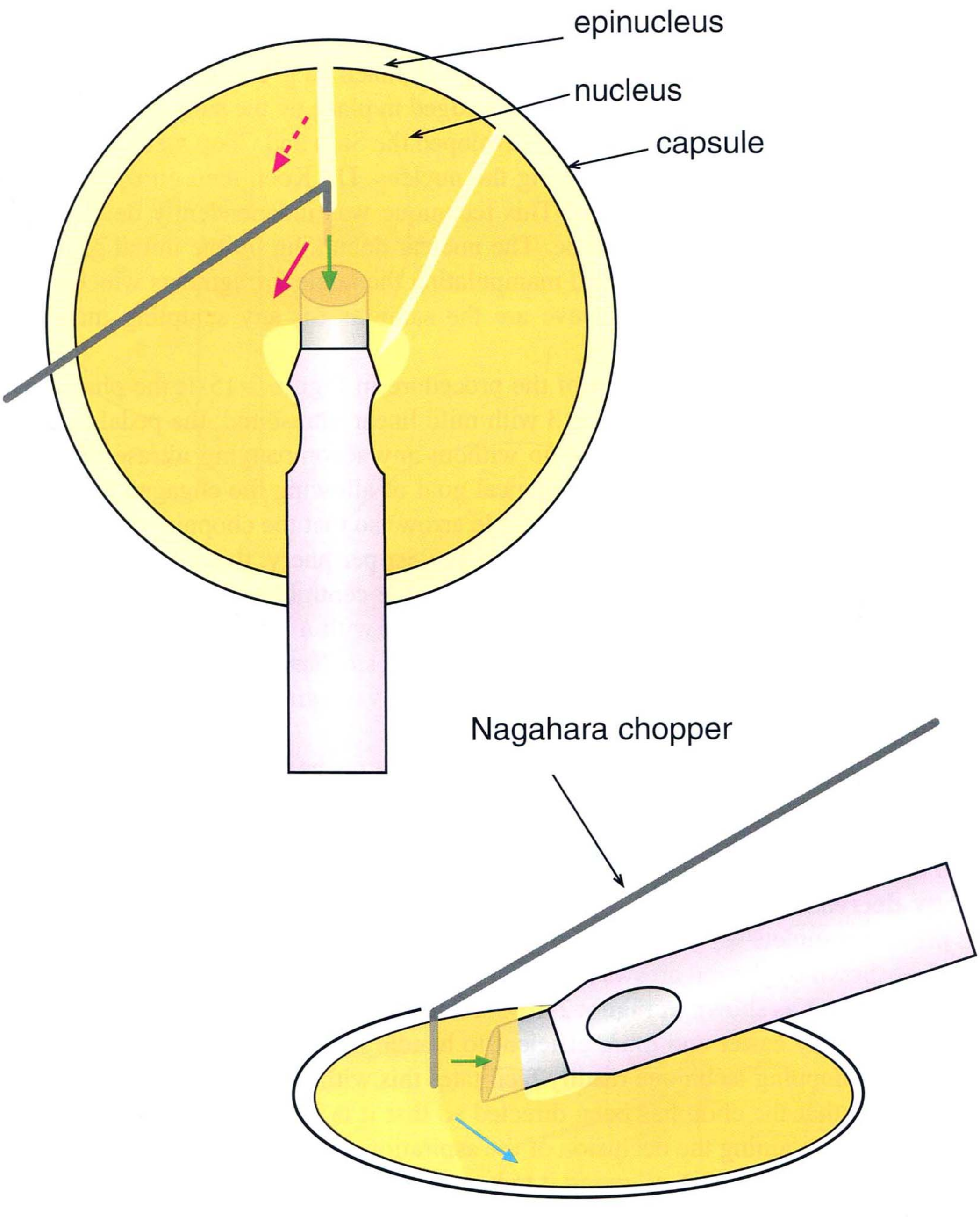


FIGURE 2-14

Modified Horizontal Chop: Stop and Chop 1

When operating on denser nuclei with the original phaco chop method, it can be difficult to remove the initial chopped segment because it is wedged in place by the surrounding intact nucleus. To overcome this problem, Dr. Paul Koch developed the Stop and Chop method, which begins by carving a central groove and then bisecting the nucleus. Dr. Koch then utilizes the chopping technique to subdivide the nuclear halves. This technique was independently developed by Dr. Ronald Stasiuk as the Mini-Chop technique. The nuclear debulking by the initial groove formation allows ample room for dislodging and manipulating the nuclear fragments which are created by chopping. Settings for the initial groove are the same as for any sculpting maneuver (see Figures 2-8 through 2-10).

In order to begin the chopping part of the procedure in Figure 2-15-1, the phaco tip enters the heminucleus in standard pedal position 3 with mild linear ultrasound; the pedal is then raised to position 2 in order for vacuum to build up without any accompanying ultrasound. Sufficient vacuum is required in order to achieve the clinical goal of allowing the engaged heminucleus to be drawn away from the periphery (see blue double arrow) so that the chopping instrument is less likely to engage capsule as it is inserted around the nuclear periphery; this maneuver is facilitated by the initial groove formation which creates space for the central heminuclear displacement. A typical **vacuum** range for this step is 200 to 260 mm Hg with a standard phaco needle; correspondingly more vacuum is needed if using a needle with a smaller distal surface area (see Figure 1-61). Remember to set an adequate **bottle height** for this vacuum level, typically 95 to 110 cm. A typical **flow rate** would be 28 to 34 cc per minute.

Vacuum should be increased if the phaco tip pulls out of the heminucleus when attempting to draw it centrally, assuming that technique was optimized both in ensuring complete initial occlusion of the aspiration port (Figure 2-6) as well as ensuring discontinuation of ultrasound as soon as the tip was embedded to an adequate depth. **Ultrasonic vibration of the phaco needle dramatically decreases its ability to grip and pull impaled fragments**. If residual posterior adhesions prevent complete separation of the chopped fragment, the phaco tip and the chopper can be separated as shown by the red arrows in Figure 2-15-2, resulting in the ready-to-carousel positioning of the fragment as shown in Figure 2-15-3. Note that the chopped fragment is smaller than a quadrant. It is usually easier and more efficient to handle smaller segments when dealing with harder nuclei; the chopping technique readily facilitates this without the need for carving multiple grooves. Also note that the chop has been directed so that it is completed just to the side of the phaco tip, thereby maintaining the occlusion of the aspiration port (ie, vacuum seal); positive control of the fragment is maintained, allowing it to be manipulated into optimal position in preparation for carouseling emulsification. Recall that this method requires somewhat more vacuum and grip than drawing the chopper directly to the phaco tip (Figure 2-14), and therefore needs a correspondingly higher bottle height.

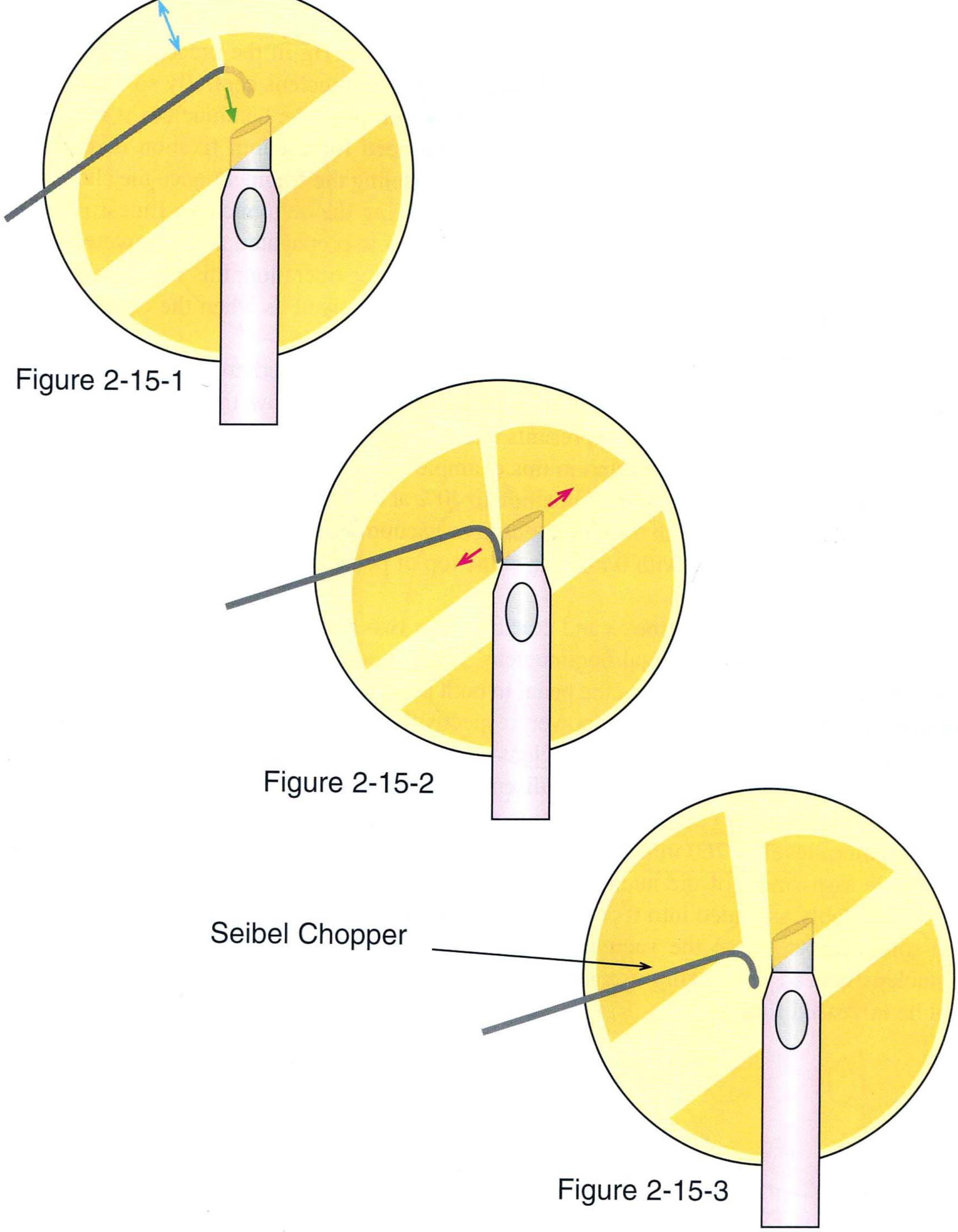


FIGURE 2-15

Modified Horizontal Chop: Dynamic Linear Parameter Adjustment

Recall that high vacuum in the range of 200 to 260 mm Hg in the preceding paragraph is required for gripping and mobilizing the relatively large heminucleus centrally so that the chopper can safely engage the heminuclear periphery. However, once the heminucleus is mechanically fixated between the chopper and the phaco tip, the need for vacuum fixation is diminished. Furthermore, typically less vacuum is required for carouseling the fragment once the chop is completed relative to the higher vacuum required for mobilizing the heminucleus. Linear pedal control will allow dynamic reduction of vacuum as the chop is propagated and completed so as to maintain the appropriate vacuum level for each moment of the operation; this will maximize safety by reducing the propensity for surge during carouseling as well as when the chop happens to break the vacuum seal (aspiration port occlusion).

Dual Linear Pedal control has the advantage of allowing linear control of vacuum independent of linear ultrasound control. The schematics in Figure 2-16 show the video overlay of the Bausch & Lomb Millennium, which represents not only the actual level of parameters but also the actual position of the pedal. Ultrasound in this example is set up in the yaw position of the pedal, with a range from 0 at the center neutral position to 40% at the right limit of lateral travel. Vacuum (either commanded vacuum with a vacuum pump or vacuum limit with a flow pump) is set up on the pitch motion of the pedal, with 0 mm Hg at the top of pedal travel and 260 mm Hg at the bottom.

After a central sculpted groove and cracking into two heminuclei, the surgeon embeds the phaco tip into the face of the distal heminucleus, using moderate amounts of vacuum and ultrasound; note the midrange position of the pedal in both pitch and yaw, resulting in 130 mm Hg actual vacuum and 20% actual ultrasound power, respectively (Figure 2-16-1). Once the tip is buried, the clinical goal is to mobilize the heminucleus centrally to facilitate placement of the chopper at the periphery. Therefore, the ultrasound is discontinued completely (center neutral pedal position without yaw displacement) because a vibrating needle does not grip well, and vacuum is increased to the maximum level of 260 mm Hg (full depression of the foot pedal), which was set based on preoperative assessment of the nuclear density (see Figure 2-16-2). If nuclear material abruptly and uncontrollably aspirated into the tip without ultrasound at this level, then the pedal would be raised somewhat to titrate the vacuum lower (Figure 3-31C), and if the tip pulled out of the heminucleus instead of drawing it centrally at 260 mm Hg, then the maximum vacuum setting would be increased further.

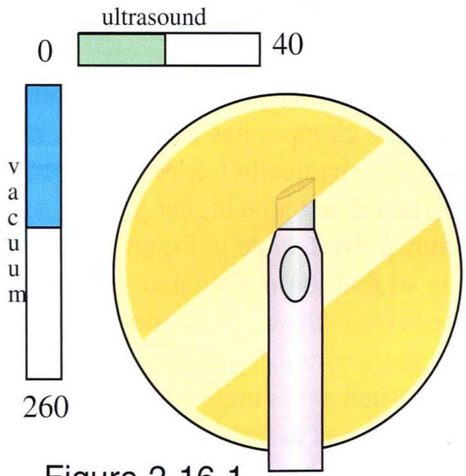


Figure 2-16-1

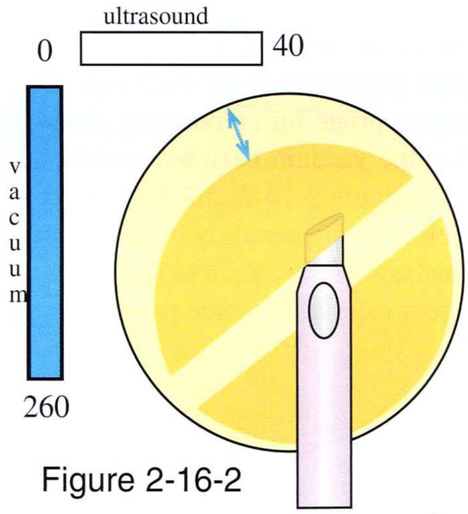


Figure 2-16-2

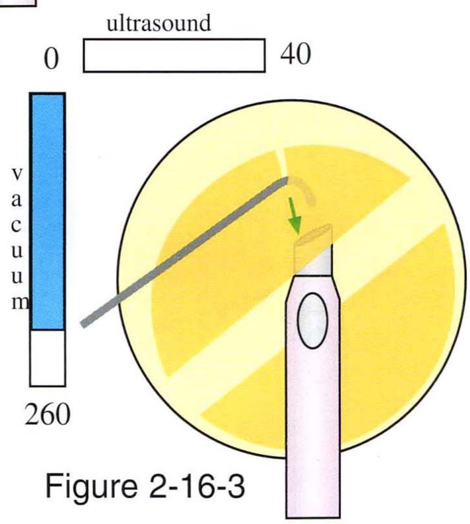


Figure 2-16-3

FIGURE 2-16A

Modified Horizontal Chop: Dynamic Linear Parameter Adjustment (continued)

The need for highest grip and vacuum in a Stop and Chop technique is during the central mobilization of the relatively massive heminucleus; once the chopper has engaged the periphery and is drawn toward the phaco tip, the engaged nucleus is mechanically trapped between the two instruments, and the vacuum can be correspondingly decreased; note the higher pedal position and lower vacuum level in Figure 2-16-3 as compared to Figure 2-16-2. Note in Figure 2-16-4 how the chopper has been drawn to the side of the phaco needle so that the maintained vacuum seal and grip can be used to laterally separate any residual adhesions (red arrows). This method of the chopper approaching the tip slightly away from the center of the aspiration port can induce a destabilizing torque (see Figure 2-6-1), and it therefore requires sufficient vacuum for gripping; note how the vacuum level is maintained in Figure 2-16-4 at the same level as Figure 2-16-3.

If the surgeon had drawn the chopper directly toward the phaco tip, there would not be an induced torque, and the vacuum could have been lowered during the chop to the carouseling level shown in Figure 2-16-5. This moderate level of about 120 mm Hg with midlevel depression of the pedal is then coupled with a yaw movement to the midrange of phaco power, a moderate level of about 20%; these settings are appropriate for carouseling phaco aspiration of this particular free-floating chopped fragment. Had the vacuum been maintained at the same high level needed for mobilization of the heminucleus (Figure 2-16-2), the propensity for surge would have been much greater. Although chopping methods may certainly be performed well with a standard foot pedal, the foregoing Phacodynamic analysis of the Stop and Chop technique with Dual Linear Control is a helpful overview of the different roles of machine parameters at different stages of surgery.

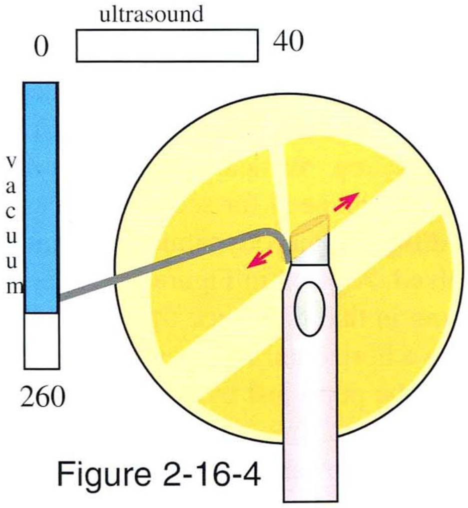


Figure 2-16-4

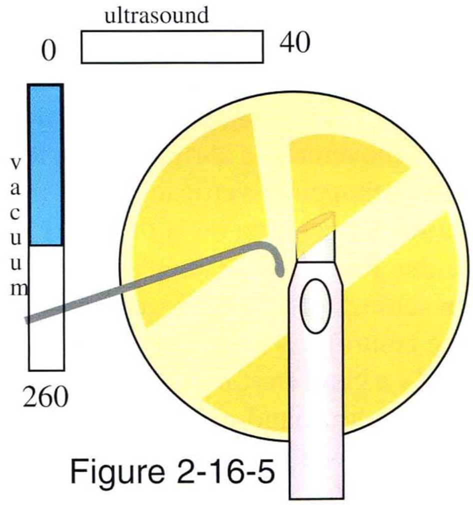


Figure 2-16-5

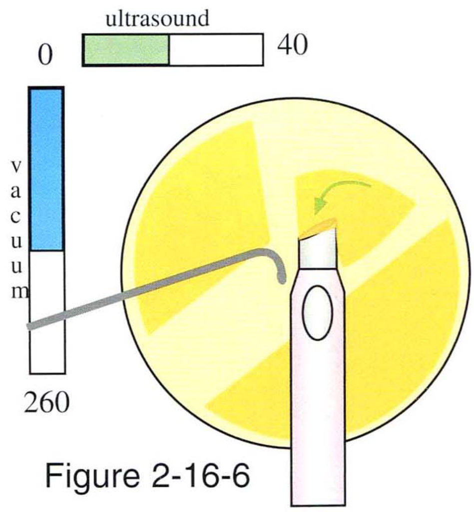


Figure 2-16-6

FIGURE 2-16B

Vertical Chop Settings 1

Vertical chopping was introduced as the Snap and Split Technique by Dr. Hideharu Fukasaku, followed by almost simultaneous descriptions by Dr. Vladimir Pfieffer (Phaco Crack) and Dr. David Dillman (Quick Chop). Like horizontal chopping, vertical chopping utilizes mechanical shear force via the chopper to decrease or eliminate the need for sculpting to subdivide the nucleus. However, vertical chopping has somewhat different Phacodynamic requirements than horizontal chopping due to different vector forces involved. As seen in Figure 2-17, vertical chopping starts out in a similar manner to horizontal chopping in that the phaco tip is embedded into the center of the nucleus. However, rather than dissecting a horizontal chopper to the nuclear periphery, the vertical chopper is placed close to the center of the pupil just in front of the phaco tip (Figure 2-17-2). It is then pushed posteriorly to fully embed it as shown in Figure 2-17-3, at which point continued downward force to the chopper and slight upward force to the phaco tip (both with only slight actual movement) create a shear force that produces the chop. A firm grip of the nucleus by the phaco needle is required for the entire vertical chop, as opposed to the horizontal chop technique in which vacuum/grip requirements are lessened once the chopper is drawn toward the phaco tip, entrapping and compressing the engaged nucleus (recall Figure 2-16-3).

Because the vertical chopping movement is at right angles to the phaco needle as opposed to directly toward it as with horizontal chopping, vertical chopping requires an even firmer grip of occluding nuclear material. **Vacuum** settings can be in the range of 250 to 350 mm Hg or higher, depending on variables such as the phaco needle dimensions as well as existing surge control mechanisms. The higher vacuum settings often require a correspondingly higher **bottle height** of 110 cm to provide adequate surge control. As with horizontal chopping and fragment removal, a **flow rate** around 28 to 34 cc/min is a good starting range. Because of the efficiency of emulsification of small chopped fragments, ultrasound power requirements are typically low on most machines, often around 30% of Pulse Mode linear power.

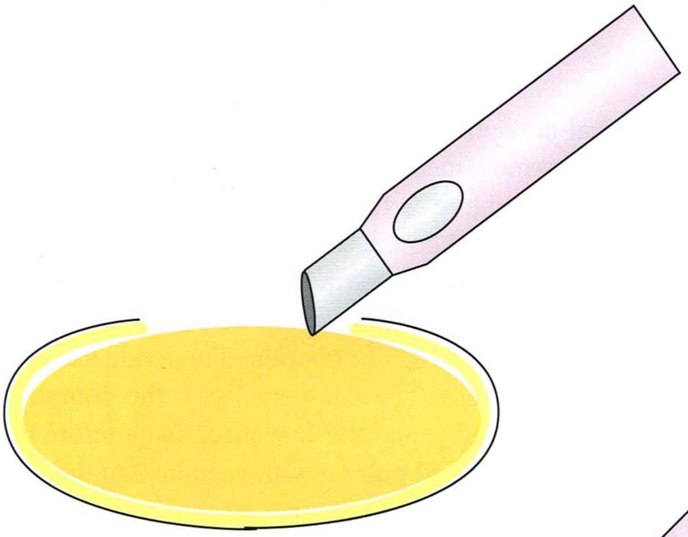


Figure 2-17-1

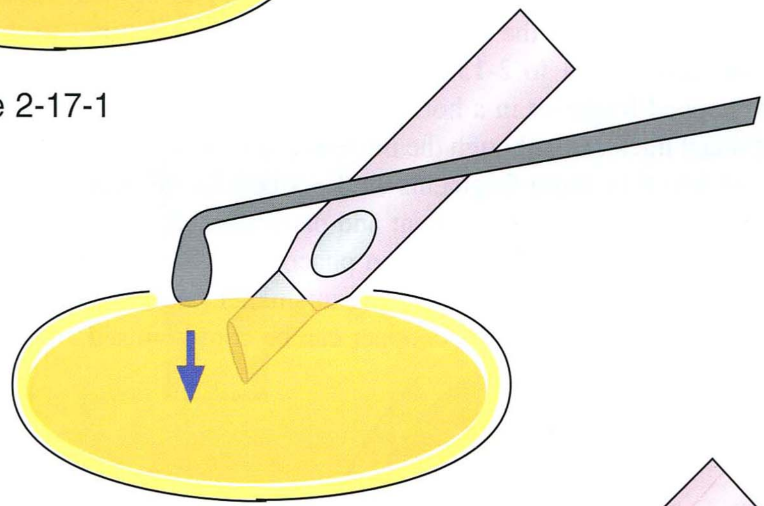


Figure 2-17-2

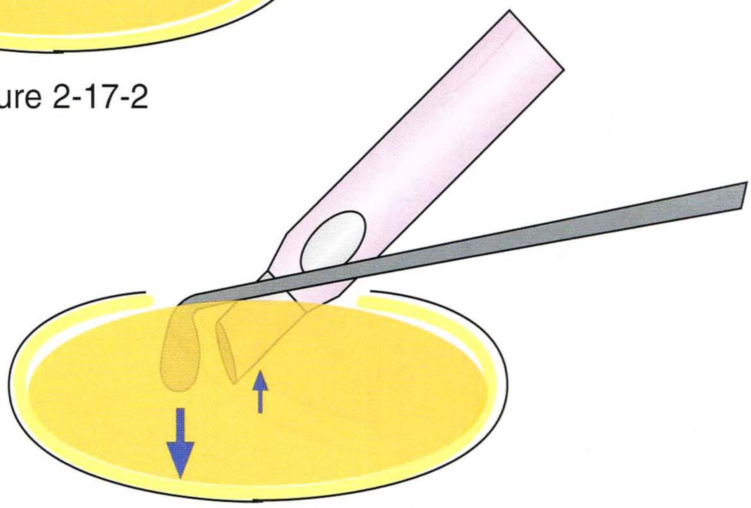


Figure 2-17-3

FIGURE 2-17

Vertical Chop Settings 2

The chopping forces created by the vertical movements shown in Figure 2-17-3 initiate the fracture line shown in Figure 2-18-1; these vertical movements are augmented by the simultaneous horizontal movement and separation shown in Figure 2-18-2. Note that the chopper was placed just at the side of the phaco tip rather than centered on the aspiration port; the subsequent fracture line is therefore less likely to break the vacuum seal and grip by the phaco needle during horizontal propagation of the chop. By slightly rotating the nucleus 45 to 60°, another chop can be quickly made to create the first fragment, and this process can be continued to divide the nucleus into 6 to 8 pieces prior to removing any one of them. The components of the completely chopped nucleus are relatively unstable in the capsular bag, and the first piece is therefore relatively easy to remove first by impaling with the phaco tip and pulling with vacuum and then phacoaspirating closer to the center of the chamber, utilizing similar settings to those described for fragment removal in Figures 2-11 to 2-13. This ease contrasts with the occasional difficulty of removing the first chopped fragment in a horizontal chop method that is held tightly in place by the residual ring of intact nucleus. Although the nucleus could conceivably also be first completely horizontally chopped into 6 or more fragments as described for vertical chopping, this is not as convenient because of the additional movement and dissection attendant to horizontal chopping. Also, note the central location of the chopper and phaco tip in vertical chopping, which is especially advantageous relative to horizontal chopping in smaller pupil cases in which visualization of the peripheral placement of a horizontal chopper can be compromised.

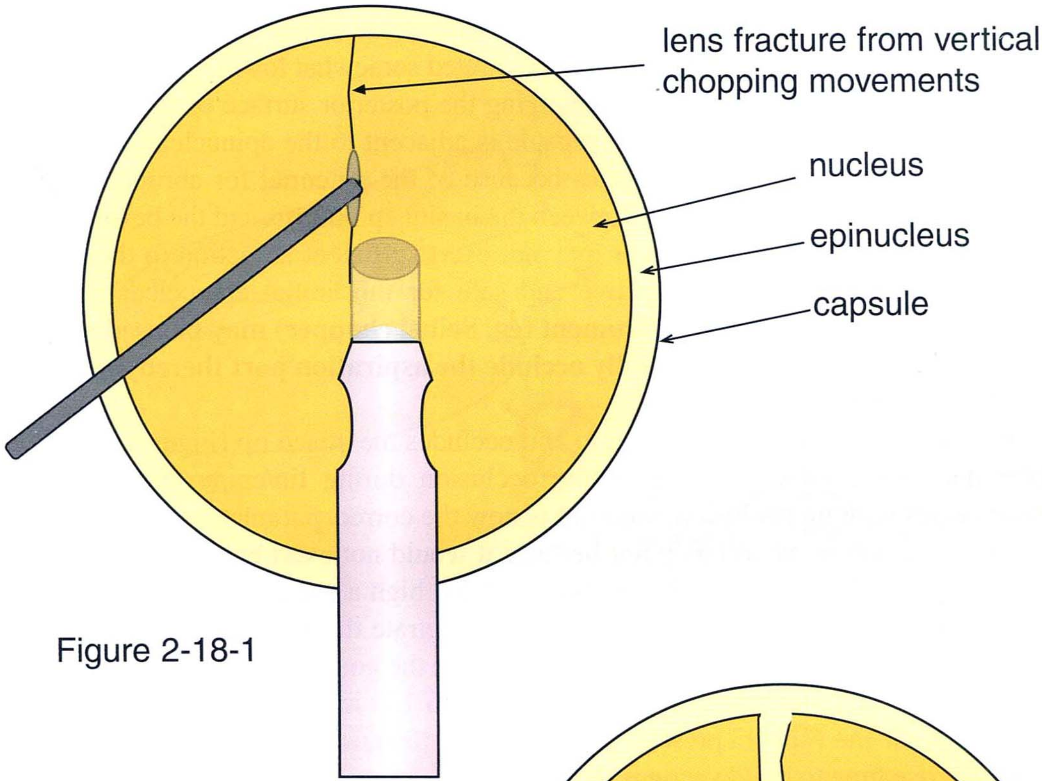


Figure 2-18-1

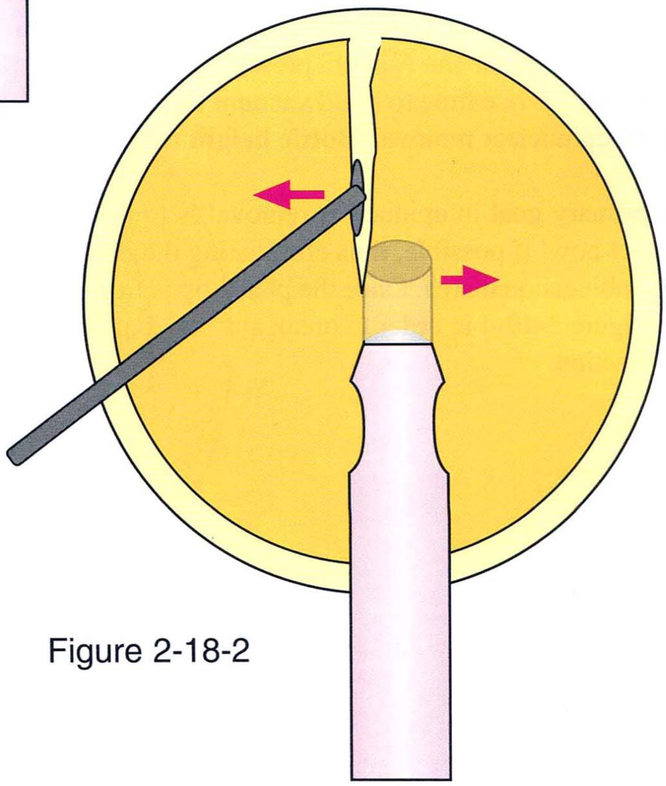


Figure 2-18-2

FIGURE 2-18

Epinucleus Settings 1

Optimal flow and vacuum settings for epinuclear removal can be similar to those used for quadrants, although vacuum levels often need to be titrated somewhat lower. Figure 2-19-1 shows the initial phaco tip positioning just prior to engaging the posterior surface of the anterior rim of the epinuclear bowl. Given the fact that the capsule is adjacent to the epinucleus at this point, it would be inappropriate to use high flow rates because of the potential for abrupt, uncontrolled aspiration. However, because of the angle between the in situ epinucleus and the bevel of the aspiration port (blue lines), very low flow rates may not exert sufficient attraction to the tip. A **flow rate** of 20 to 24 cc/min is usually effective and safe for this initial epinuclear engagement. **Additionally, a blunt-tipped second instrument (eg, Seibel chopper) may be used to mechanically manipulate the epinucleus to initially occlude the aspiration port thereby reducing the need for higher flow rates**.

Once the epinucleus has been attracted to and occludes the phaco tip (Figure 2-19-2), a sufficient force must be exerted to maintain the occlusion during tip/epinuclear manipulation. Because flow ceases with tip occlusion, **vacuum** is now the correct parameter to adjust. Low vacuum is obviously inappropriate at this point because it would not exert enough gripping force to maintain the occlusion. However, you must also avoid too high a vacuum, which would abruptly aspirate the occluding epinucleus, allowing the tip to penetrate the epinuclear bowl and threaten the capsule (Figure 2-19-3); this scenario would also fail in the goal of maintaining a positive hold on the epinuclear bowl. A moderate vacuum level of 80 to 120 mm Hg is often effective, but do not hesitate to increase the vacuum preset if you are unable to maintain a positive hold on the bowl after allowing for rise time to build vacuum after occlusion. Linear vacuum control in phaco mode is ideal for epinuclear removal. **Bottle height** for this vacuum level is typically in the range of 80-90 cm.

A primary goal in epinuclear removal is to free it from the surrounding capsule and cortex as an intact bowl if possible, thus eliminating the need for chasing after multiple pieces, especially in the subincisional area. Once the phaco tip is firmly engaging the epinucleus, the bowl is rotated as in Figure 2-19-4 in order to break any residual adhesions which sometimes remain even after hydrodissection.

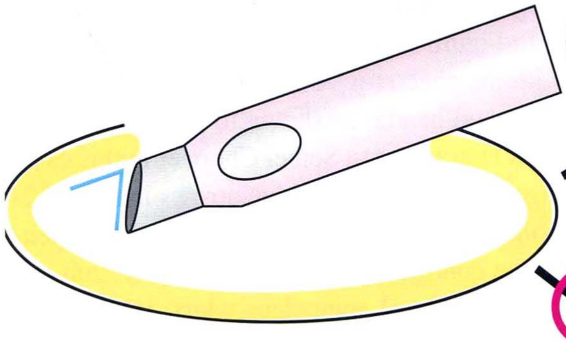


Figure 2-19-1

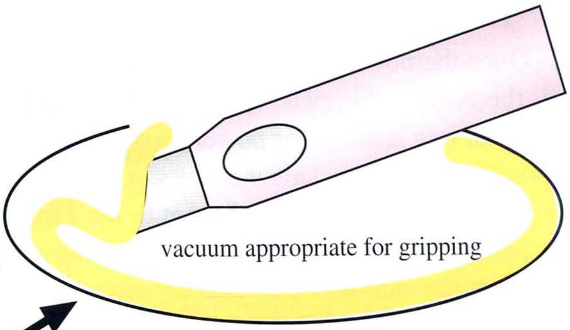


Figure 2-19-2

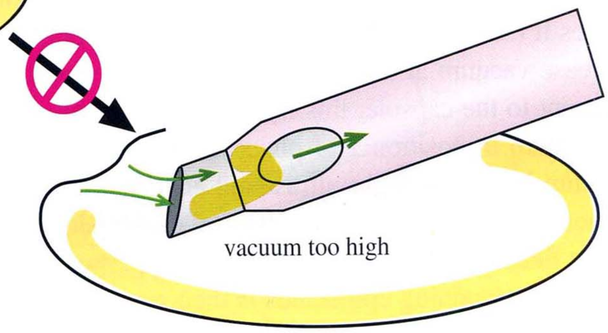


Figure 2-19-3

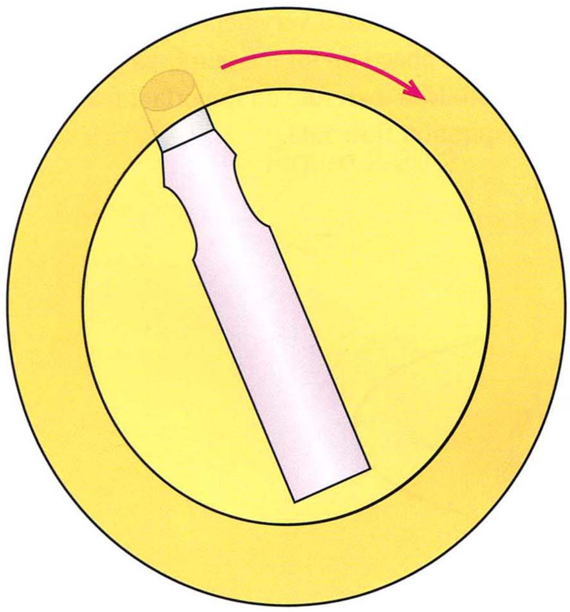


Figure 2-19-4

FIGURE 2-19

Epinucleus Settings 2

Once the bowl's perimeter and posterior surface have been freed by rotation as in Figure 2-19-4, the bowl is "flipped" (per Dr. I. Howard Fine) so that aspiration and emulsification (Pulse Mode with low level linear power recommended) can take place at the iris plane or the middle of the posterior chamber. This increases your safety margin by avoiding aspiration or emulsification of the epinucleus when it is adjacent to the capsule. In Figure 2-20-1, the contraincisional epinuclear bowl has been pulled away from the capsule with the phaco tip. A second instrument inserted through the side-port can then be used as a fulcrum and handle as shown to pull the subincisional bowl inferiorly and flip the epinucleus over. This instrument (a Seibel Chopper in this case) should engage the epi-nucleus over a sufficiently large surface area (see blue arrows in Figure 2-20-1) such that the instrument's force pushes and manipulates the epinuclear bowl rather than penetrates it (see Figure 3-16). Once you have obtained the configuration in Figure 2-20-2, you can increase vacuum at this point to deform and aspirate the engaged epinucleus which is no longer adjacent to the capsule; this is especially convenient if the machine has linear foot pedal control of vacuum in position 2 of phaco mode. Alternatively, you can augment the original (gripping) vacuum level with light ultrasound energy to emulsify the part of the bowl engaged by the tip. Choosing the latter strategy achieves a safer, slower flow rate with a vacuum pump and decreases the likelihood of a surge with any pump.

The remaining epinucleus is then reengaged to repeat the process as necessary as shown in Figure 2-20-3. Just as quadrant/fragment control and aspiration depended on precise and appropriate titration of the vacuum level, epinuclear removal is also very dependent on proper vacuum to allow proper control of the epinuclear bowl by the phaco tip for the purposes of gripping as well as aspirating; linear control of vacuum in phaco mode is therefore an important feature on a phaco machine, even more so than linear control of aspiration flow rate.

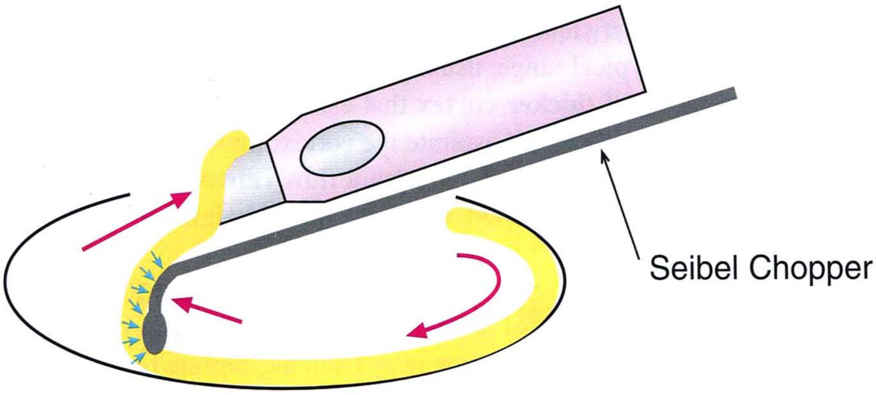


Figure 2-20-1

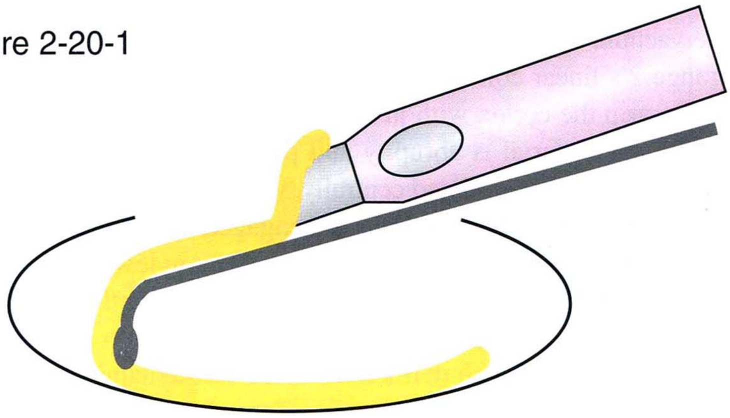


Figure 2-20-2

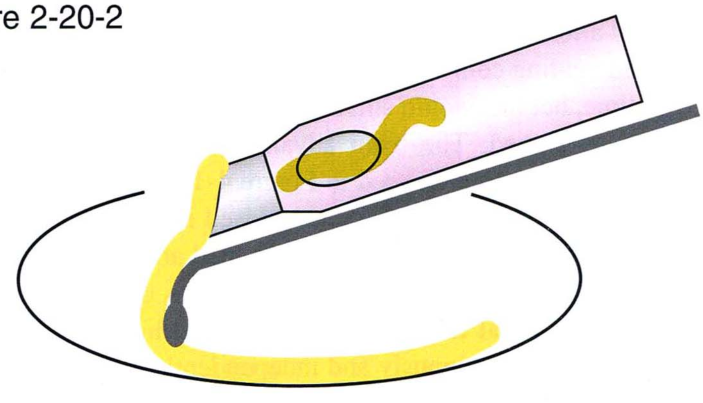


Figure 2-20-3

FIGURE 2-20

Cortical Removal Settings

Aspiration of **thin cortex** relies on sufficient **flow rate** to cause enough friction to aspirate the cortical strands; 35 to 45 cc/min is a typical range, usually coupled with a maximum vacuum setting of 350 to 400 mm Hg. Aspiration of **thicker cortex** that can completely occlude the IA aspiration port relies more on **vacuum** to deform and aspirate the cortex; maximum levels of 400 to 500 mm Hg with linear control are typically used, often with a **flow rate** of 30 to 35 cc/min. Because outflow is restricted by the small aspiration port, moderate **bottle heights** of 70 to 85 cm are typically adequate.

In IA mode, some flow pumps offer the option of either linear pedal control of flow (ie, rotational speed of the pump head) or linear pedal control of vacuum. Linear vacuum control is effective when the surgical goal is to engage cortex for stripping away from the capsule by slow movement of the engaging IA tip as shown in Figures 2-21-1 and 2-21-2. Figure 2-21-3 illustrates what would happen if the vacuum in Figure 2-21-1 were increased excessively by depressing the foot pedal too far into range 2's linear control of vacuum (note more red bars on vacuum meter); the object in this case is to grip the cortex with just enough force (vacuum) to allow positive control but not so much force that material is abruptly and prematurely aspirated. With the cortex dissected away from the capsule and mobilized centrally, vacuum can subsequently be increased (eg, to the level in Figure 2-21-3) to safely aspirate the engaged cortex. If the surgeon prematurely pushes the pedal only slightly past the optimum gripping vacuum level (eg, material just begins to aspirate through the port), then the linear pedal pressure can be slightly reversed to reestablish an appropriate gripping level of vacuum. The foregoing logic of vacuum adjustment is an extension of the discussion with Figure 1-4, which defined distinct Phacodynamic clinical goals of gripping and aspiration.

Contrast this scenario to that of linear flow control, under which vacuum could not be decreased after it started to cause premature aspiration of cortex (other than with a return to position 1 and venting completely back to zero vacuum). Linear flow control would allow titration of the rise time, but this would still not allow diminution of vacuum once the optimum gripping level had been surpassed. The main advantage of flow control is for dealing with thin strands of diaphanous cortex as discussed in Figure 4-1. Perhaps the most effective mode of control is with a vacuum pump (or with a flow pump used in vacuum emulation). In these cases, grip could be precisely titrated to thick cortex as discussed above, and grip and flow would **autoregulate** with thin cortex as a function of applied vacuum as discussed with Figure 4-1 (see also Figure 2-5). Alternatively, a Dual Linear Pedal could be utilized with a flow pump so that both vacuum and flow could be simultaneously and independently adjusted as necessary.

Note that Figure 2-21-3 depicts the actual vacuum at the moment of occlusion break and aspiration of cortex; the actual vacuum will subsequently decrease with the decreased resistance through the subsequently unoccluded aspiration port.

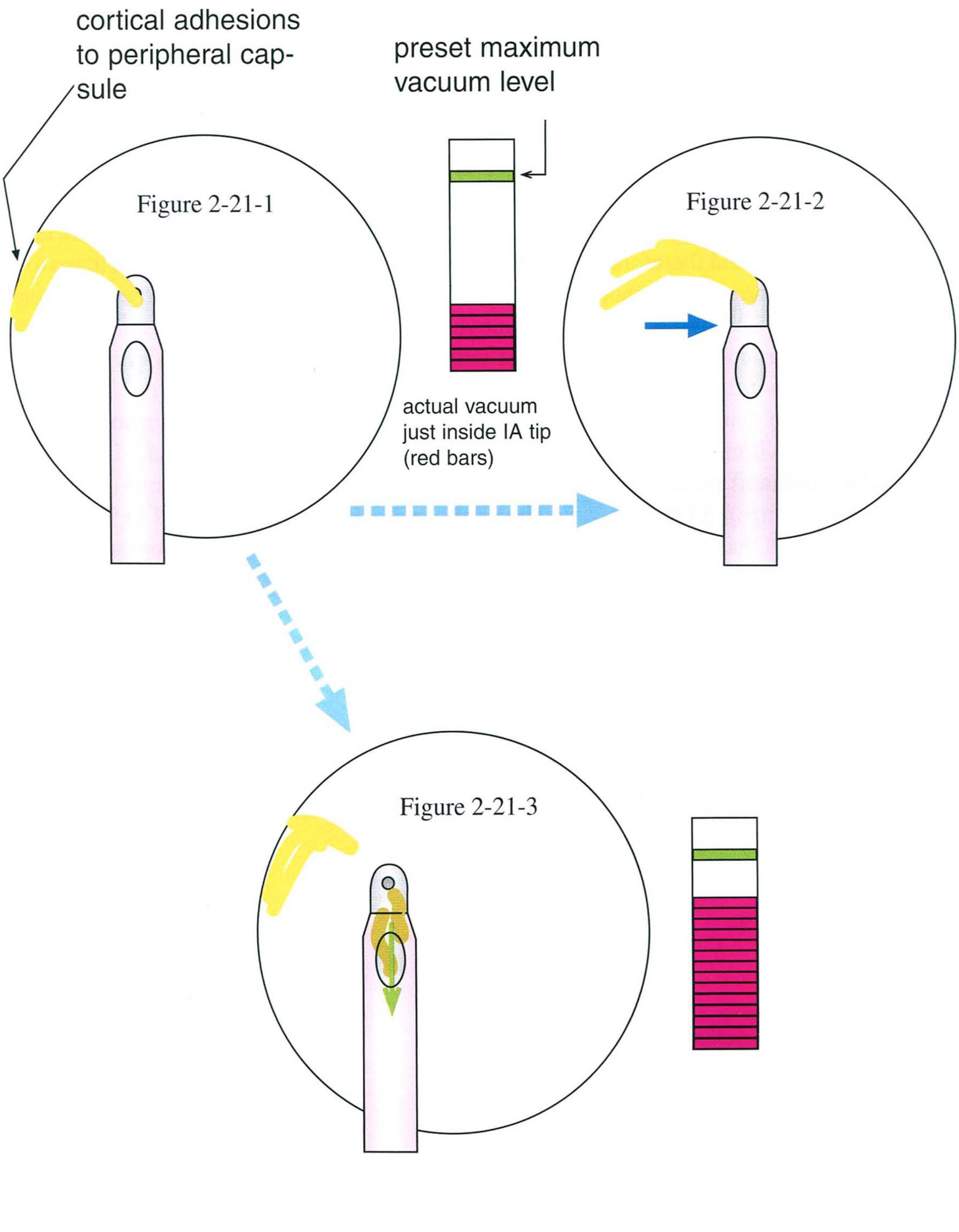

cortical adhesions to peripheral cap-sule
preset maximum vacuum level
Figure 2-21-1
Figure 2-21-2
actual vacuum just inside IA tip (red bars)
Figure 2-21-3

FIGURE 2-21

Viscoelastic Removal Settings

After implanting the lens under the protection of viscoelastic, this material is removed from the eye to reduce the incidence of postoperative elevations of intraocular pressure. Viscoelastics, more recently termed Ophthalmic Viscosurgical Devices (OVDs) by world expert Dr. Steve Arshinoff, differ in their rheologic properties and therefore behave differently during their removal. Cohesive viscoelastics (eg, Healon, Healon GV, Provisc) tend to mobilize as a whole and therefore are readily removed (Figure 2-22-1). Dispersive viscoelastics such as Viscoat tend to break apart piecemeal and therefore need higher flow rates to induce sufficient turbulence to dislodge and mobilize the material (note greater number of shorter curved blue arrows in Figure 2-22-2 relative to 2-22-1). Similarly, a viscoadaptive material such as Healon 5 requires sufficient flow and vacuum to induce fracture lines that will allow disintegration and mobilization of the material, whereupon it then behaves similarly to the dispersive OVDs.

Because of the clarity of most viscoelastics, visual feedback for phacodynamic parameter adjustment is more limited than with phacoemulsification of lens material and IA of cortex. Therefore, Dr. Arshinoff recommends 450 mm Hg **vacuum** (limit with flow pumps or commanded with vacuum pumps), 35 to 45 cc/min **flow rate** (with flow pumps), and 80 to 90 cm **bottle height** as parameters that will work well for removal of most viscoelastics in most surgical situations. Supplemental techniques for turbulence creation and OVD removal include periodic axial rotation of the handpiece (and therefore variation of flow pattern from irrigation ports) as well as cycling between pedal positions 1 and 2. Additionally, Dr. Arshinoff's "Rock and Roll" method of OVD removal utilizes the IA tip to gently manipulate the IOL to help dislodge trapped viscoelastic.

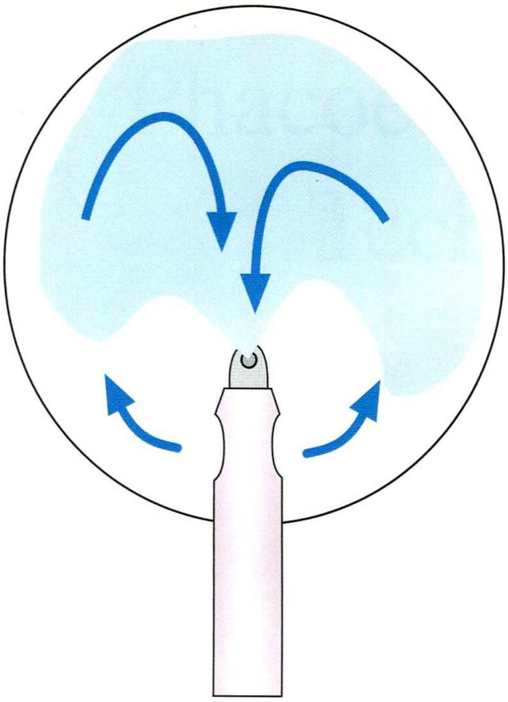


Figure 2-22-1

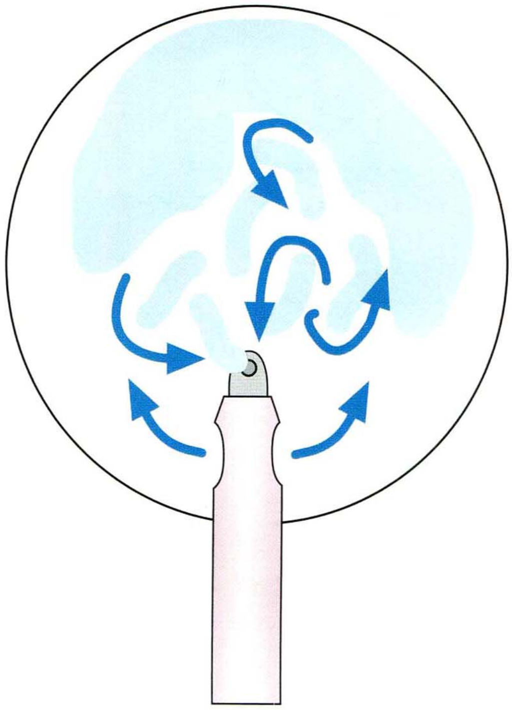


Figure 2-22-2

FIGURE 2-22

SECTION THREE

Overview of Phacoemulsification Techniques

Overview of Phaco Methods

The following method descriptions are relatively brief synopses; refer to the Bibliography for complete descriptions by the methods' originators and proponents.

Nuclear Segmentation

Also known as a chopping, cracking, or splitting technique, the basic idea behind this method is to mechanically fracture the cataract into two or more pieces which can be more easily and efficiently manipulated and attracted to the phaco tip as opposed to a single whole nucleus. Moreover, safety is enhanced because the nuclear segments can therefore be emulsified in a carouseling fashion in the posterior chamber or iris plane as opposed to emulsifying the nucleus completely by sculpting in its in vivo position juxtaposed to the capsule. The use of mechanical force through a side-port instrument for nuclear subdivision reduces the overall amount of ultrasound energy required for the operation, thereby accelerating postoperative visual rehabilitation.

Dr. Howard Gimbel originally described bisecting the nucleus as the **Divide and Conquer Method**; Dr. John Shepherd extended the technique to the **4-Quadrant Method** (see Figure 2-11), a version of which is described as follows. Begin with a capsulorrhexis; then use hydrodissection and hydrodemarcation to facilitate nuclear rotation. Begin phacoemulsification by sculpting a deep groove. Rotating the nucleus 180° is often necessary to complete this groove. The nucleus is then split into halves at the base of the groove. Rotate the two halves 90° to carve a groove into the middle of one of them. Perform a second fracture here and then phaco the two quadrants separately after drawing them safely to the middle of the posterior chamber or the iris plane. Repeat this procedure on the remaining nuclear half. The epinucleus is then removed, if possible, as an intact bowl utilizing the phaco tip as discussed in Figures 2-19 and 2-20.

Fault-line phaco is a technique that I developed to exploit the design attributes of the Flat-Head Phaco tip. It differs from the classic quadrant procedure in that the "grooves" are actually channels within the body of the nucleus which are created by a more efficient occlusion mode boring as opposed to sculpting. The channels can also be used as a precursor to chopping.

Dr. Kunihiro Nagahara developed the original **phaco chop** technique, which is now classified as a **horizontal chop** technique per Dr. David Chang. As described in Figure 2-14, the nucleus is impaled by the phaco tip while a phaco chop instrument is used to split the nucleus into multiple fragments, which are then safely emulsified in the center of the posterior capsule or iris plane. This procedure readily facilitates making multiple nuclear segments which are smaller than full quadrants; the smaller segments are easier to handle and are more readily emulsified in a carouseling motion with fewer manipulations by a second instrument, especially with denser nuclei.

Sometimes it can be difficult to dislodge the first nuclear fragment because it is wedged into place by the surrounding nucleus. To overcome this problem, Dr. Paul Koch developed his **Stop and Chop** method, which is described in Figures 2-15 through 2-16B (independently developed by Dr. Ronald Stasiuk as the **Mini-Chop** method). The initial groove formation allows sufficient room for dislodging and manipulating the nuclear halves as well as the fragments that were created by chopping.

A more recent variation of Phaco Chop is the group of **vertical chop** techniques, including Dr. Hideharu Fukasaku's **Snap & Split**, Dr. Vladimir Pfieffer's **Phaco Crack**, and Dr. David Dillman's **Quick Chop**. These methods utilize a vertical shear force and central instrument placement as opposed to horizontal chopping (see Figures 2-17 and 2-18). Dr. David Chang deserves credit for classifying the various chopping techniques into the clinically relevant categories of horizontal and vertical.

Some generalizations can be made when comparing chopping techniques to cracking techniques. For example, horizontal chopping tends to stabilize the nucleus between the tip and the chopping instrument. Furthermore, with both horizontal and vertical chopping, mechanical force is directed centripetally as the chopping instrument cleaves the nucleus. Therefore, minimal force is directed outward against the capsule periphery. Contrast this to cracking methods, during which the nuclear periphery is pushed outward against the capsule by the cracking instruments; any defect in the capsulorrhexis is therefore at greater risk for peripheral and posterior extension with cracking as opposed to chopping. Chopping is also a more efficient method than cracking with respect to ultrasound power expenditure because chopping uses mechanical force for nuclear segmentation as opposed to sculpting grooves; furthermore, ultrasound during chopping is most often applied in the more efficient occlusion mode (see Figure 1-50). Finally, chopping is a more time efficient method than cracking in that a segmenting chop can be made with a single instrument movement as opposed to multiple ultrasonic sculpting passes required for a groove; also, the smaller chopped fragments are more readily emulsified in a carouseling fashion with less repositioning required relative to larger quadrants (see Figure 3-36).

Two-Handed Technique

This designation actually applies to several methods, including most of the nuclear segmentation techniques. One hand manipulates the phaco handpiece while the other hand manipulates a second instrument, such as a cyclodialysis spatula, nucleus rotator, nucleus cracker, or chopping instrument. This second instrument is inserted through a side-port incision and is used to move the nucleus into optimum position for phacoemulsification. This "two-handed" designation would of course also apply to Bimanual Microincision Phaco (see Figure 1-2), which often employs chopping or cracking methods. Although a two-handed technique is a virtual necessity for nuclear subdivision methods, it is often associated with Dr. Richard **Kratz's method** (popularized by Dr. William Maloney) of central sculpting followed by removal of the nuclear rim; this is followed by pushing inferiorly at the contra-incisional nuclear rim so that the sub-incisional rim can be prolapsed anteriorly and emulsified. The nucleus is then rotated and more rim is removed until only a nuclear plate remains. This plate is often free-floating and is emulsified by allowing it to carousel into the phaco tip. This sculpting-intensive method typically requires significantly more ultrasound energy for a given cataract than the occlusion-intensive methods such as chopping.

In contrast, Dr. David Brown's **Phaco Flip** method uses primarily the more efficient occlusion-mode phacoemulsification after the nucleus is primarily prolapsed into the anterior chamber without any preliminary sculpting. A variation of Phaco Flip is Dr. Richard Lindstrom's **Tilt and Tumble** method. These methods particularly depend on corneal endothelial protection by viscoelastic in order to prevent excessive postoperative corneal edema secondary to direct nuclear contact as well as ultrasound energy delivered in the anterior chamber.

The Kratz method was originally described utilizing a can-opener type **capsulotomy**, which facilitated nuclear prolapse. However, this type of capsulotomy has several disadvantages. The loose tags of capsule often interfere with cortical removal by clogging the aspiration port. More importantly, it can lead to posterior capsular tears via extension along one of the anterior capsular can-opener tears. These difficulties can be eliminated by employing a continuous tear capsulotomy, or **capsulorrhexis**, as described originally by Dr. Howard Gimbel and Dr. Thomas Neuhann. Although it is possible to perform a two-handed nuclear prolapse technique with a capsulorrhexis, as is recommended with Phaco Flip, it can be difficult if the capsulorrhexis diameter is insufficient. However, this Phaco Flip requirement of a relatively large capsulorrhexis diameter is at odds with the recommendation for a sufficiently small capsulorrhexis (5 to 5.5 mm) that will overlap the anterior IOL edge to help prevent Posterior Capsule Opacification by pushing a posterior square optic edge into the posterior capsule to inhibit central lens epithelial cell migration (research by Dr. Okihiro Nishi).

In some cases involving a relatively large capsulorrhexis, a thick epinucleus, and a distinct, smaller, inner nucleus, you can employ hydrodemarcation to prolapse the inner nucleus into the anterior chamber or iris plane. In these cases, this small inner nucleus can be emulsified by carouseling without rim removal or other manipulations. This is essentially Dr. Howard Fine's **Chip and Flip** method in which emulsification of the hydrodemarcated inner nucleus (the chip) is followed by removal of the epinuclear bowl by engaging the 6 o'clock anterior rim and pulling superiorly so as to flip it upside down in preparation for emulsification.

One-Handed Technique

Dr. Robert Sinskey originally developed this technique; it had been popularized by Dr. Marc Michelson and Dr. Richard Livernois. The method's name is a misnomer in that both hands are usually used to manipulate the phaco handpiece; a more appropriate name would be "Single-Incision Technique". Because there is no side-port incision or second instrument, all nuclear manipulations are performed with the phaco tip. Deep central sculpting is followed by nuclear rim removal and rotation, and ultimately by nuclear plate removal. Although the theoretical advantage of this method is additional control of the phaco handpiece, I feel that it is outweighed by the disadvantage of losing the additional nuclear manipulating capability afforded by a second instrument through a separate incision.

Applying Fundamentals to All Methods

Sections One and Two have stressed the importance of appropriate machine parameter settings. Surgical technique is not only just as important, but is moreover integrally related; as stressed throughout section 2, technique should always be optimized before adjusting the machine technology. Smooth sculpting which avoids nuclear movement and zonular stress is critical to all methods. Well-controlled deep and peripheral sculpting facilitates cracking in segmentation methods and rim removal in one- and two-handed methods. By using just enough ultrasound power to embed the phaco tip and then backing off to the IA position (standard pedal position 2), the nucleus can be positively engaged for rotation, manipulation, etc; this extra versatility of the phaco tip (gripping in addition to phacoaspiration) is especially important for one-handed techniques as well as chopping techniques. The principles of mechanical advantage apply to all methods; safety is maximized by using the minimum force and movement required to accomplish a given task. Many of the examples and illustrations that follow depict a segmentation method, but each example is not so much a step in a phaco method as it is an illustration of a fundamental concept which is often applicable to multiple methods. By understanding these concepts, the surgeon will be able to transpose as necessary between methods, improvise new methods, and adapt to virtually any surgical situation.

Sculpting Angle of Attack

As discussed previously, the ultrasonic needle operates like a jackhammer with oscillations occurring in an axial fashion as indicated by the green arrows. If the long axis of the needle were placed parallel to the surface to be sculpted as in Figure 3-1-1, the needle would simply vibrate back and forth over the surface without sculpting. Figure 3-1-2 shows how introducing an angle of attack takes advantage of the axial direction of needle vibration so that each vibration bites into the surface to be sculpted.

The bottom three figures illustrate a clinical application of the above principle. This is a **side-view cross-section** of a typical contour of a groove or bowl that is about two thirds completed. Note that areas A and B readily lend themselves to further sculpting given the favorable angle of attack. However, area C presents the same unfavorable tip to surface configuration as Figure 3-1-1. Area C can be readily sculpted if the nucleus is rotated 180° so that C is moved to the area formerly occupied by A; the contraincisional position presents an optimum angle of attack and allows for completion of the groove, which is in turn a prerequisite for efficient nuclear cracking, which is in turn required for many nuclear subdivision methods.

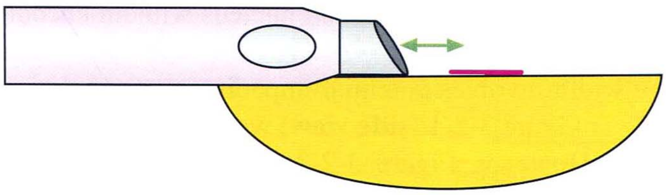


Figure 3-1-1

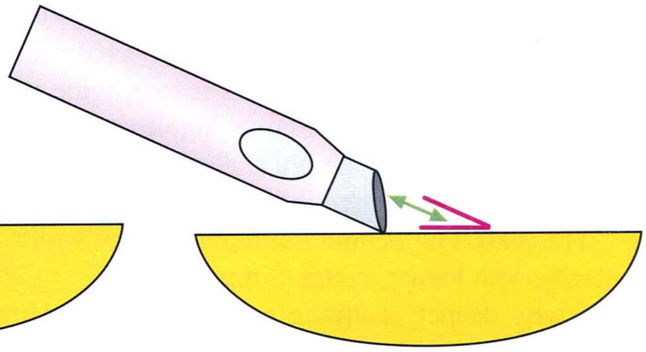


Figure 3-1-2

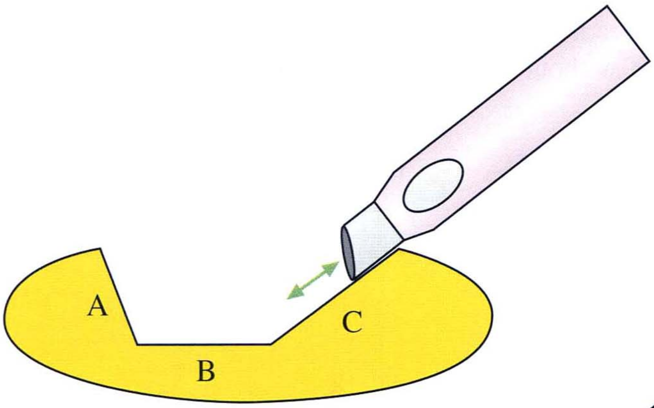


Figure 3-1-3

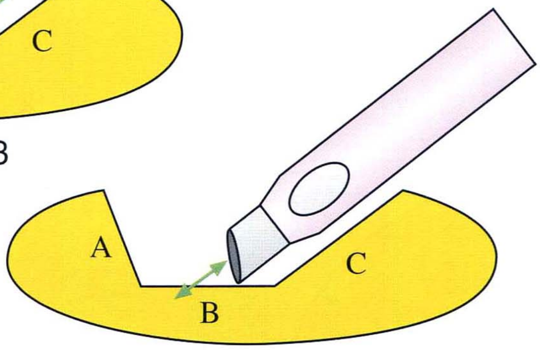


Figure 3-1-4

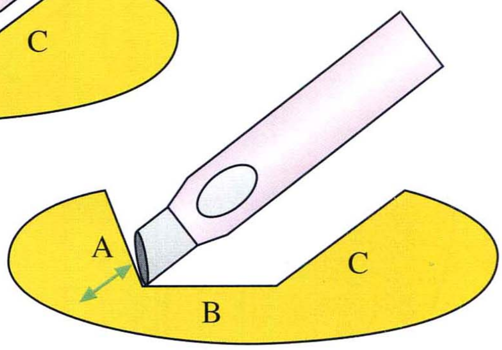


Figure 3-1-5

FIGURE 3-1

Minimum Groove Width

A rough rule of thumb for most phaco methods is that harder nuclei can potentially be sculpted more completely (ie, debulked) in early phases of the procedure. The rationale for leaving more nucleus initially with soft cataracts is to provide more of a handle with which to manipulate the nucleus in subsequent steps. For example, if a very wide groove is sculpted in a soft nucleus, the second instrument may simply cheese-wire through the little remaining nucleus without encountering enough resistance to induce nuclear rotation.

The reasoning behind minimum groove width involves potential impediments to sculpting, especially with harder nuclei. Simply glancing at Figure 3-2-1 (**side view**) would not indicate any reason why deeper sculpting could not occur. However, Figure 3-2-2 (**front and top views**) reveals that the phaco needle's silicone sleeve will not fit into the narrow groove. Always be aware of this potential obstruction. Otherwise, you may try to compensate by using unnecessarily high ultrasound power or pushing the handpiece harder and stressing zonules. Neither of these solutions will overcome the problem; you simply have to widen the groove before proceeding deeper as depicted in Figure 3-2-3. This maneuver readily exposes the floor of the groove to further sculpting by the emulsifying action of the tip without obstruction from the nonemulsifying silicone sleeve on the sides of the groove.

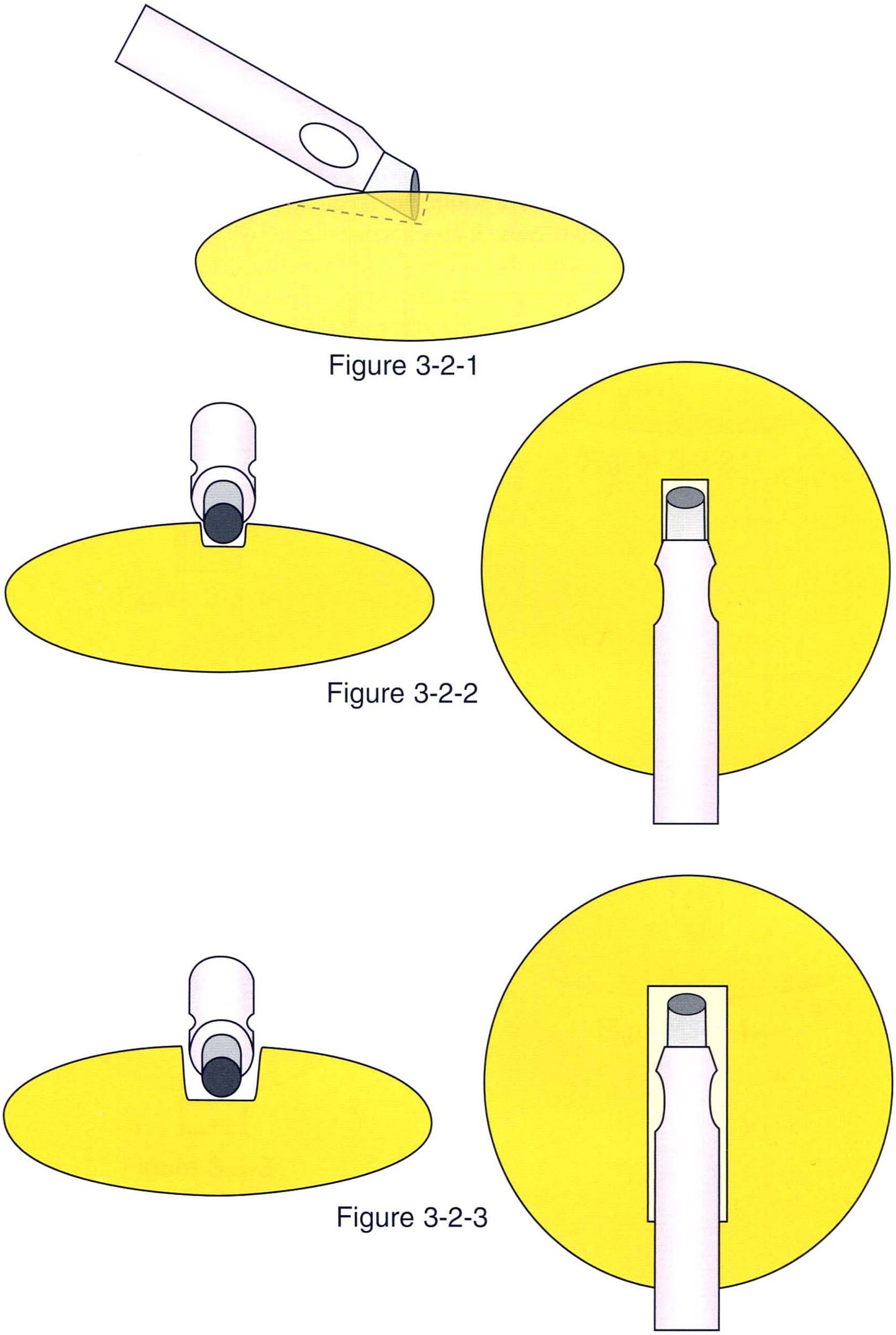


FIGURE 3-2

Posterior Groove

Although the groove may be wide enough for the complete phaco tip and sleeve (Figure 3-3-1), the posterior contour may be such that it obstructs the silicone sleeve (see red arrows) and prevents further posterior sculpting (Figure 3-3-2). This is simply an extension of the concept of maintaining an adequate minimum groove width, but it can be more misleading when more than half of the groove depth is sculpted because it appears that the groove width is adequate from your anterior microscope's perspective since the sleeve seems to be fitting down into the groove. Only by careful attention to the posterior contour can this potential pitfall be noticed and rectified as in Figures 3-3-3 and 3-3-4. The techniques utilized to correct the posterior contour are essentially the same as those used to widen the peripheral groove contour in Figure 3-8.

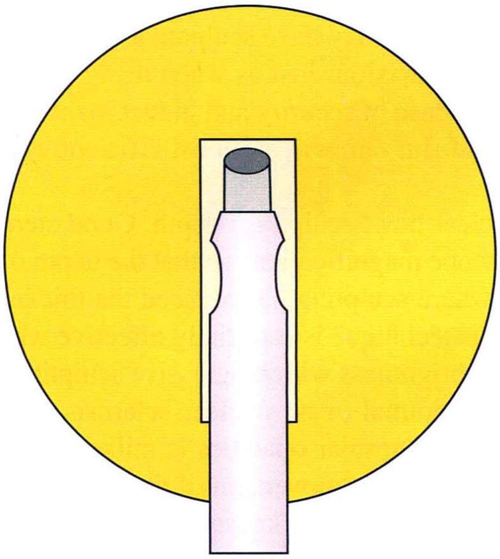


Figure 3-3-1

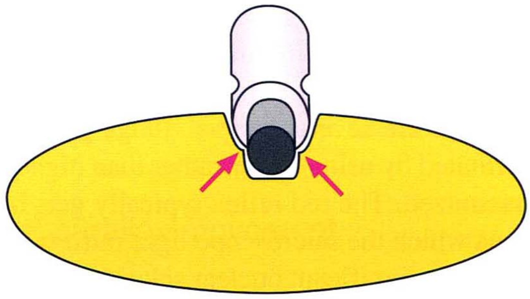


Figure 3-3-2

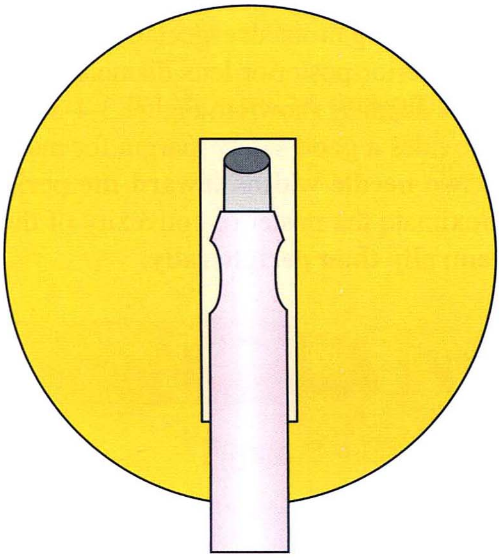


Figure 3-3-3

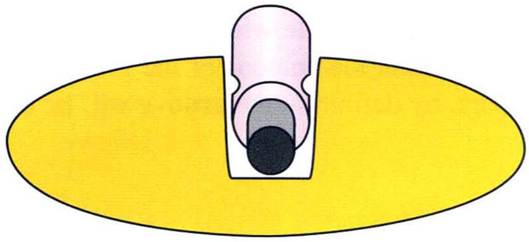


Figure 3-3-4

FIGURE 3-3

Judging Groove Depth

One of the most prominent fears of the beginning phaco surgeon is sculpting too deeply and inadvertently rupturing capsule. The tendency is to think one may have sculpted a Grand Canyon, when in reality the nucleus received little more than an abrasion. Just as when using insufficient phaco power, sculpting inadequately gives only a false sense of security and in fact makes all subsequent steps more difficult; both nuclear cracking and rim removal are most efficiently accomplished after deep sculpting.

There are several ways to judge groove (or nuclear bowl sculpting) depth. Good stereopsis is facilitated by using lower rather than higher microscope magnifications so that the depth of field is maximized. The red reflex typically gets brighter where sculpting has reduced the thickness of nucleus which the microscope light must traverse. This technique is especially effective when the cataract has significant nuclear sclerosis; the change in brightness with progressive sculpting is not as evident with a posterior subcapsular opacity with minimal or no nuclear sclerosis. A useful technique for judging depth with posterior cortical or subcapsular opacities is utilizing parallax; gently manipulate the nucleus from side to side and observe the movement of the posterior opacities relative to the base of your groove. With decreasing nuclear thickness separating the groove base and the opacities, the opacities will move less relative to the groove base with induced parallax (Figures 3-4-1 and 3-4-2).

The groove depth can be directly measured using the phaco needle as the unit of measurement. Recall that a standard phaco needle is approximately 1 mm in outer diameter (Figure 1-61); the surgeon should know the measurement for any needle being utilized, especially the smaller 20 Ga. or 21 Ga. micro-needles. Since the average adult anterior-posterior lens diameter is about 4 mm, the phaco needle can be used to estimate the groove depth as shown in Figure 3-4-3. A measure that accounts for possibly thick epinucleus and provides a good safety margin for most cases is **two to three needle widths centrally** and **one to two needle widths toward the periphery**. Remember that the contour of the groove must approximate the posterior convexity of the lens; therefore, by definition the **groove will be deeper centrally than peripherally**.

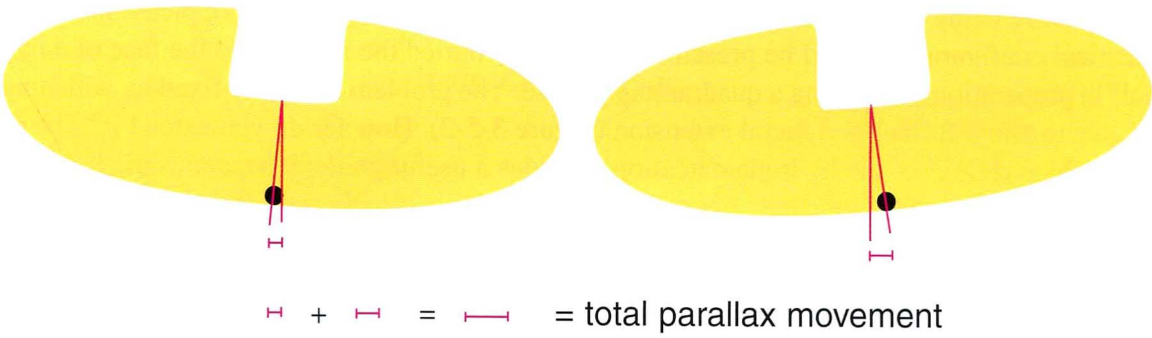
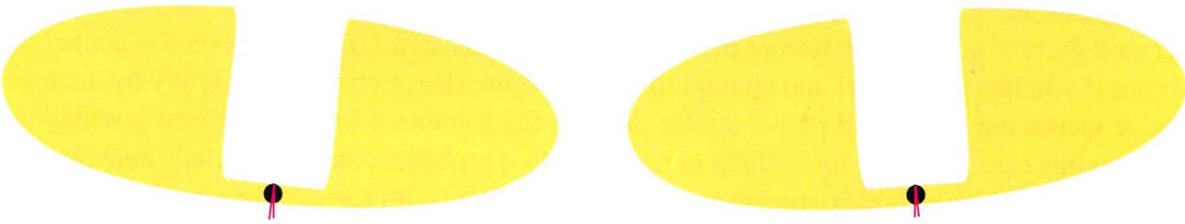


Figure 3-4-1



total parallax movement is negligible with deep sculpting

Figure 3-4-2

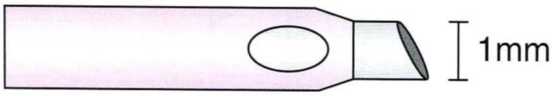


Figure 3-4-3

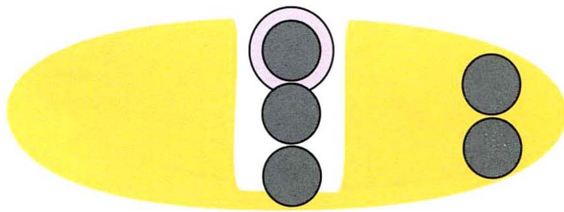


FIGURE 3-4

Peripheral Groove

Figure 3-5-1 depicts a physical impediment to further peripheral sculpting because of the silicone sleeve being obstructed by too narrow a peripheral groove (red arrows); please note that this identical configuration could be present if you simply buried the needle into the face of a nuclear half in preparation for making a quadranting groove. The problem is readily fixed by widening the groove to allow further peripheral extension (Figure 3-5-2). How far do you extend it? The circular "golden reflex" of the hydrodemarcation provides a useful guide; it separates the harder inner nucleus from the soft epinucleus. Because the epinucleus is usually removed relatively easily as a pliable bowl at the end of phacoemulsification, it is unnecessary to sculpt into it beforehand; moreover, the epinucleus serves to keep the capsule protected and formed, and should therefore be left intact and undisturbed for as much of the operation as possible. The object of initial sculpting in any method is to prepare the inner nucleus for fracturing or rim removal. Therefore, the hydrodemarcation reflex marks a functional limit for peripheral extension (of the groove in a cracking method or of central sculpting in a Kratz method or one-handed method).

In Figure 3-5-3, the above objectives have been accomplished. Although the silicone sleeve would obstruct further peripheral sculpting, there is no need to widen the peripheral groove because there is no need for further peripheral groove extension. There are several potential outcomes if you ignore this fact and attempt to overcome the sleeve obstruction simply by maintaining or increasing ultrasound power and/or pushing the handpiece harder. The best possible outcome in this case would be for nothing to happen. More probable outcomes include zonular stress and tears, extension of pre-existing capsular tears (especially with can-opener capsulotomies), and creation of new capsular tears. Finally, because the phaco aspiration port is against the soft epinucleus, increasing power will likely emulsify and aspirate it, thus exposing the peripheral capsule to aspiration and rupture (Figure 3-5-4). The message to take home is that Figure 3-5-3 is a good endpoint for peripheral extension of a groove (either half or quadrant).

Notwithstanding the foregoing, some cataracts may crack sufficiently with the groove just short of the hydrodemarcation line, as in Figure 3-5-1. If cracking does not occur at this point, the groove can be extended to the line as described, but not beyond it.

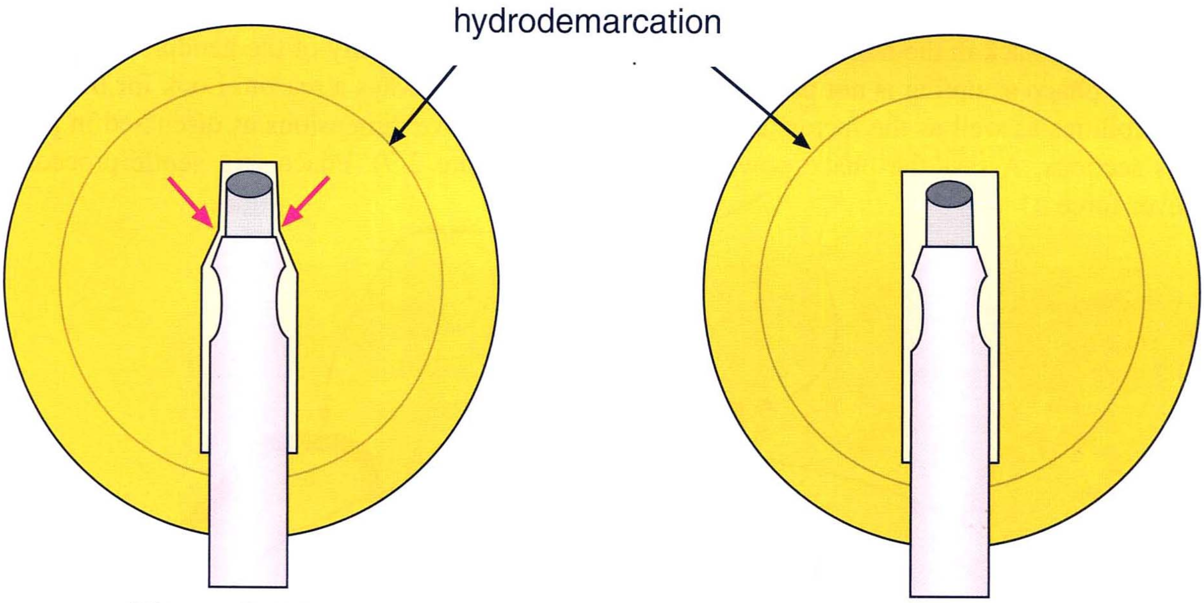


Figure 3-5-1

Figure 3-5-2

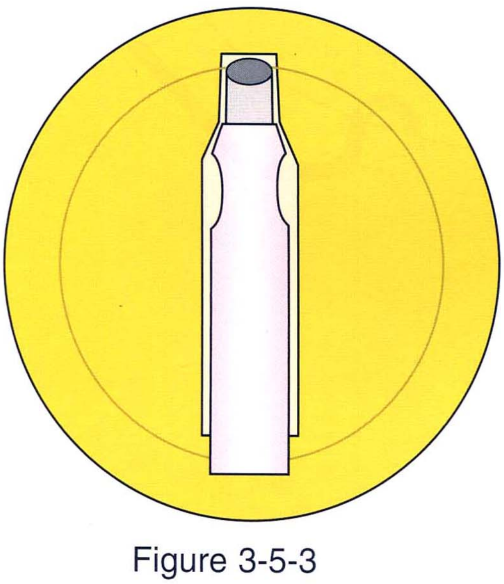


Figure 3-5-3

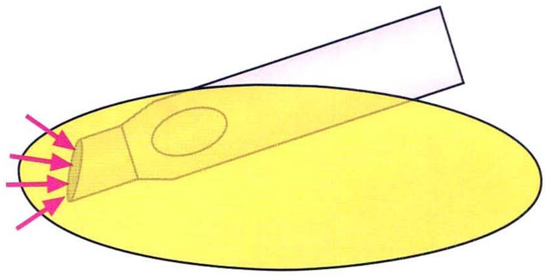


Figure 3-5-4

FIGURE 3-5

Physical Obstructions to Sculpting

The silicone sleeve is not the only physical impediment to free movement of the phaco needle. A decentered or misshapen lid speculum can catch on the hub of the phaco tip as illustrated in Figure 3-6 (red arrow). Similarly, the hub or handpiece can run into a fold of the lid drape. Insufficient slack in the handpiece tubing can also limit your mobility of the handpiece.

If phaco sculpting is not proceeding smoothly, there is always a reason. Look for the above possibilities as well as the factors concerning adequate groove dimensions as discussed in previous sections. Assess the phaco power variables (see Figure 2-9). Phaco is a gentle procedure; never force it!

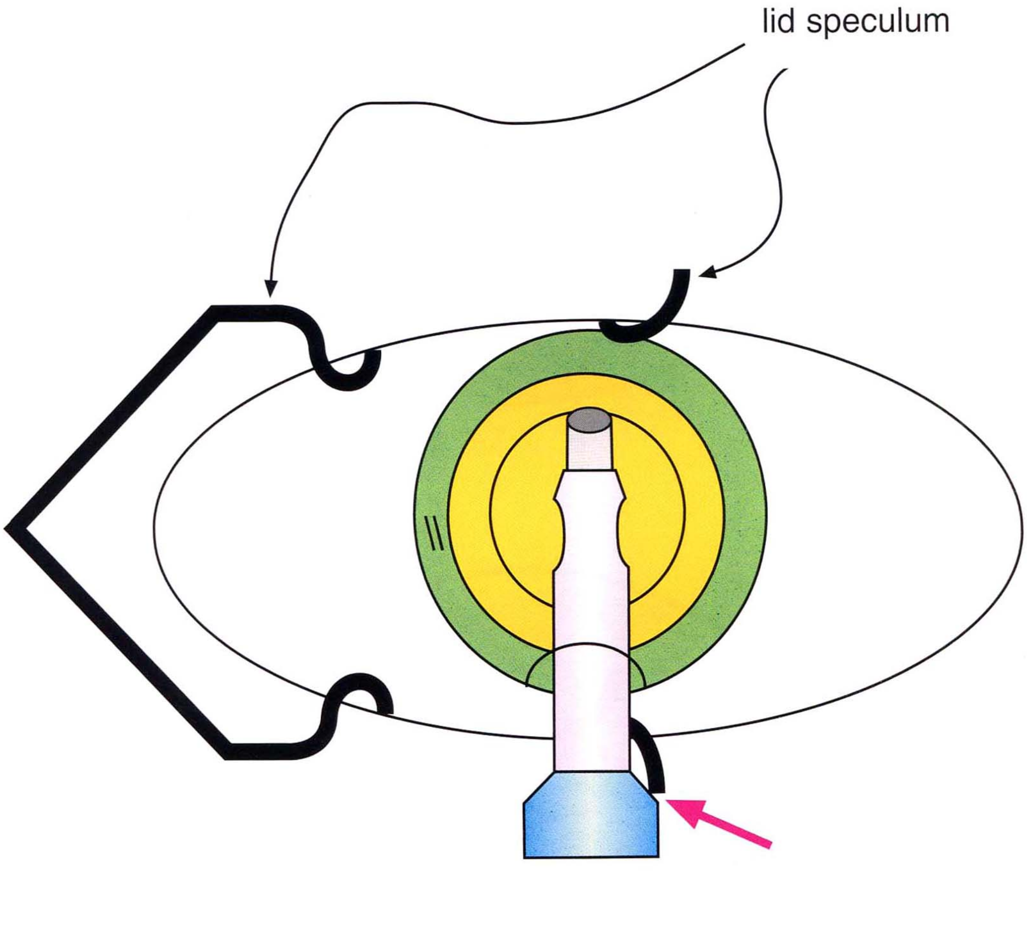


FIGURE 3-6

Use Low to Moderate Scope Magnification

Most beginning phaco surgeons err on the side of overmagnification; the rationale behind this false sense of security is that it focuses the surgeon's concentration. It is precisely this concentrated focus which leads to problems by limiting awareness of other aspects of the procedure. Note how the limited field of view with high magnification in Figure 3-7-1 does not readily reveal the cause of an obstruction in the tip's mobility. Figure 3-7-2 (lower magnification with wider field of view) shows that the problem is the speculum as described previously (red arrow). A wide field of view allows you to detect nuclear movement when sculpting so that you can adjust power, amount of tip engaged, or linear sculpting velocity as necessary. Capsular star folds from inadvertent aspiration and corneal stress lines from excessive wound distortion are both more evident with a wider field of view. Low magnification has an added advantage of providing increased depth of field. This will facilitate judging the depth and contour of grooves; it will also reduce surgeon fatigue by decreasing the amount of focus adjustments required.

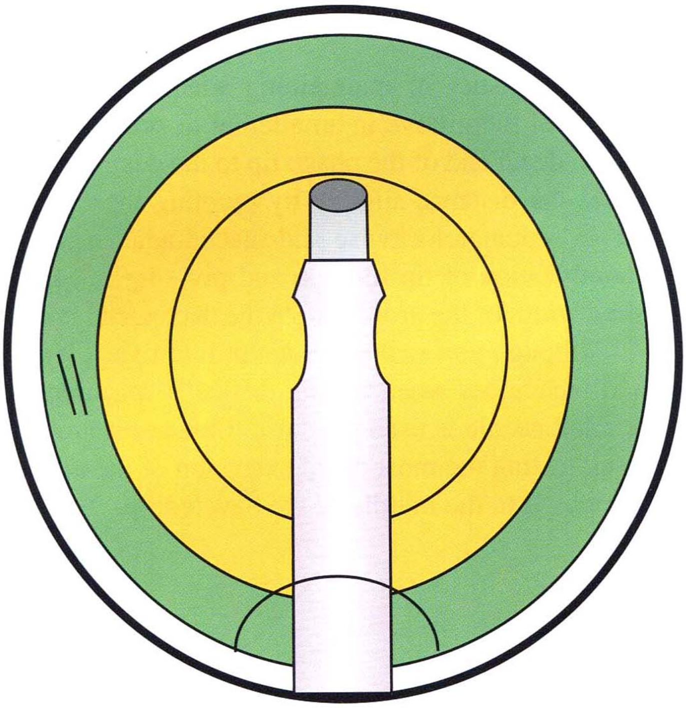


Figure 3-7-1

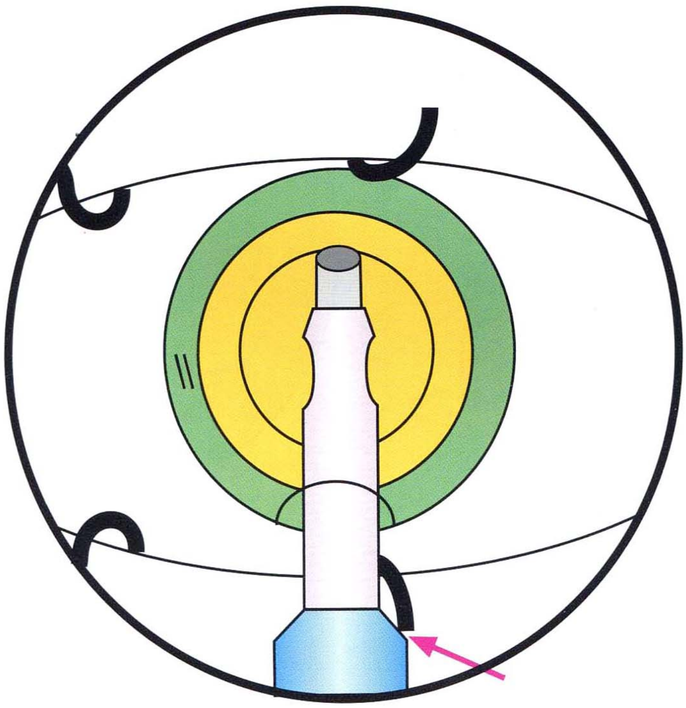


Figure 3-7-2

FIGURE 3-7

Tip Manipulations for Sculpting Groove

These figures address the logistics of maintaining adequate groove width. Figure 3-8-1 shows the phaco tip at one side of the groove in an attempt to sculpt more at the corner on that side. Note the distance from the distal end of the phaco tip to the desired endpoint of groove width (red line). Figure 3-8-2 closes the distance slightly by pivoting the tip within the groove. The handpiece has been rotated 45° counterclockwise and placed against the side of the groove in Figure 3-8-3. Finally, the combination of tip rotation and pivoting in Figure 3-8-4 achieves the closest approach to the desired width of the groove; note the decreasing length of the red line from Figure 3-8-1 through 3-8-4. Although you will often sculpt intuitively, it is sometimes helpful to remember these fundamental techniques when having difficulty reaching a particular portion of your groove. Note that a beveled needle is used for these illustrations; a 0° tip would not require any rotation as the red line (indicating the most distal extension of the tip) would be drawn to the outer edge of the 0° tip, as opposed to the middle of the beveled tip.

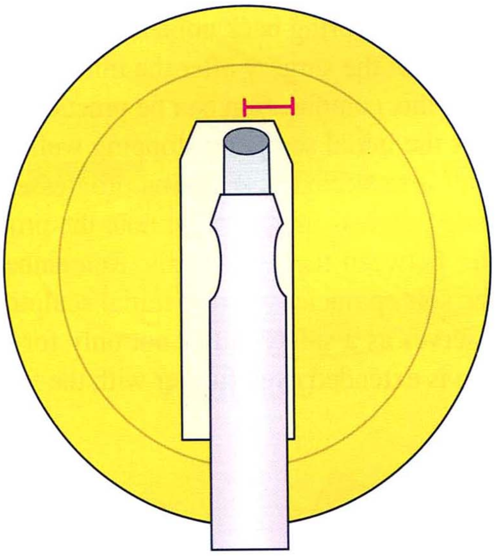


Figure 3-8-1

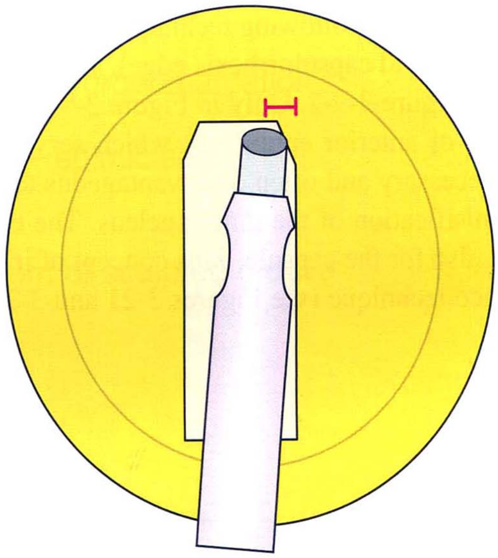


Figure 3-8-2

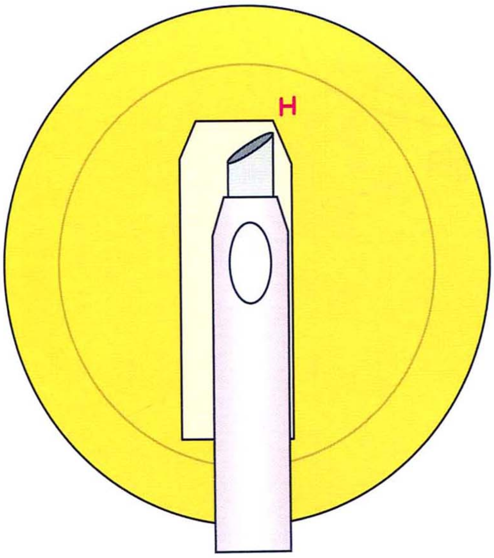


Figure 3-8-3

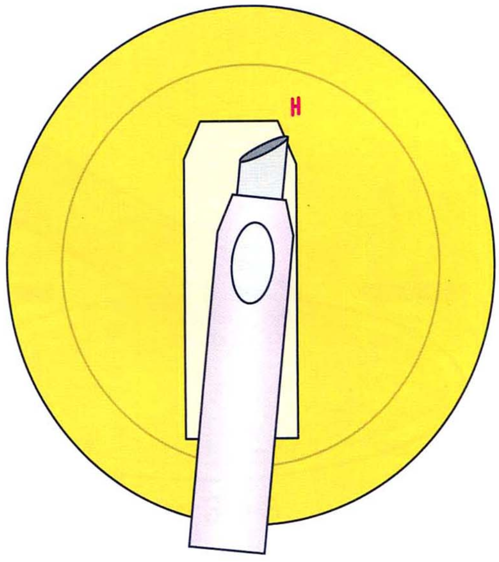


Figure 3-8-4

FIGURE 3-8

Avoiding Iris During Sculpting

Atrophic iris around the incision was once a hallmark of many early phaco cases utilizing older machines and techniques. This complication more typically shows up contraincisionally with current techniques. These patients will return to haunt you at regular postop intervals; the magnified slit-lamp view of tattered edges of atrophic iris will bring back unpleasant memories of how these edges sought out your aspiration port throughout the surgery after the initial aspiration made that whole portion of the iris floppy. Fortunately, this complication can be practically eliminated by the following technique. Figure 3-9-1 shows the initial sculpting stopping well short of the iris (and capsulorrhexis edge). This peripheral limit is respected as sculpting progresses deeper in Figure 3-9-2. Only in Figure 3-9-3 does sculpting progress peripherally; note the protective layer of anterior epinucleus which serves as a buffer between the tip and iris. Remember, it is unnecessary and often disadvantageous to remove the soft epinucleus during initial sculpting and emulsification of the inner nucleus. The epinucleus serves as a safety buffer not only for the iris but also for the capsule. This concept of iris protection is extended even further with the fault-line phaco technique (see Figures 3-21 and 3-22).

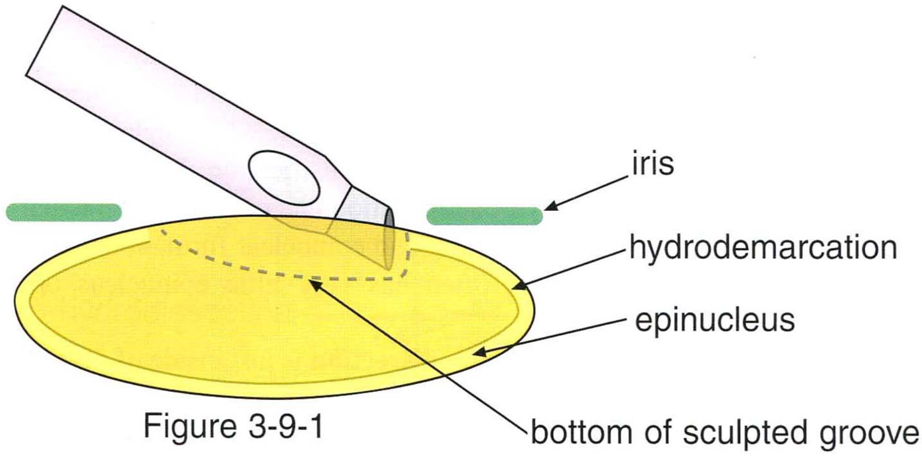


Figure 3-9-1

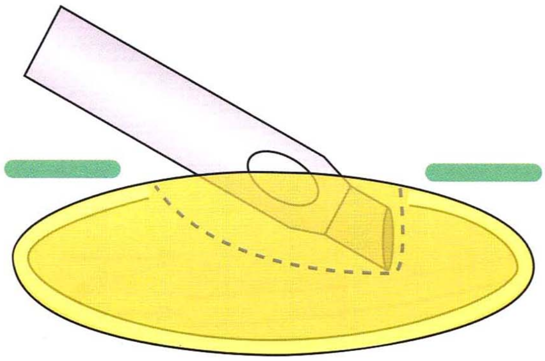


Figure 3-9-2

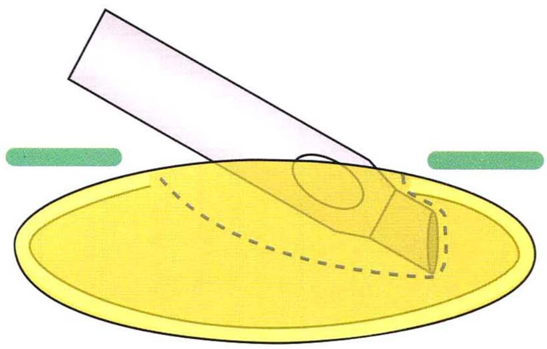


Figure 3-9-3

FIGURE 3-9

Layers of the Lens

Figure 3-10 shows a typical "lens within a lens" configuration with a distinct harder inner nucleus surrounded by a softer epinucleus; this appearance is typically evident on preoperative slit-lamp examination. An irrigation cannula is optimally introduced at the junction between the two to perform **hydrodemarcation** (also known as **hydrodelineation**), which facilitates free inner nuclear rotation. Hydrodemarcation also delineates the epinucleus, which helps to support and protect the capsule during inner nuclear manipulation and emulsification. Even relatively homogeneous nuclei are denser in the center, and hydrodemarcation can create an artifactual plane to achieve the same benefits of free inner nuclear rotation and epinuclear formation. The exception to this would be a brunescent cataract, which often has very little epinucleus or cortex—Hydrosonics® may be effective in these cases.

Note that the proper cannula placement for **hydrodissection** is just inside of the capsule; this will facilitate cortical and epinuclear removal as well as nuclear rotation. It is often helpful to initially lift the clear capsulorrhexis rim slightly off of the underlying cortex with the hydrodissection cannula. Once this step clearly defines the correct tissue plane for the cannula, the instrument and overlying capsulorrhexis rim are gently returned down to the surface of the cortex to establish a better fluid seal against backflow (see Figure 3-11-2). To the extent that the cortex is first hydrodynamically dissected, less effort is required when using the IA tip for cortical removal. Indeed, the cortex is sometimes readily removed during the aspiration of the epinucleus. Dr. I. Howard Fine coined the phrase "**cortical cleaving hydrodissection**" to describe this methodology.

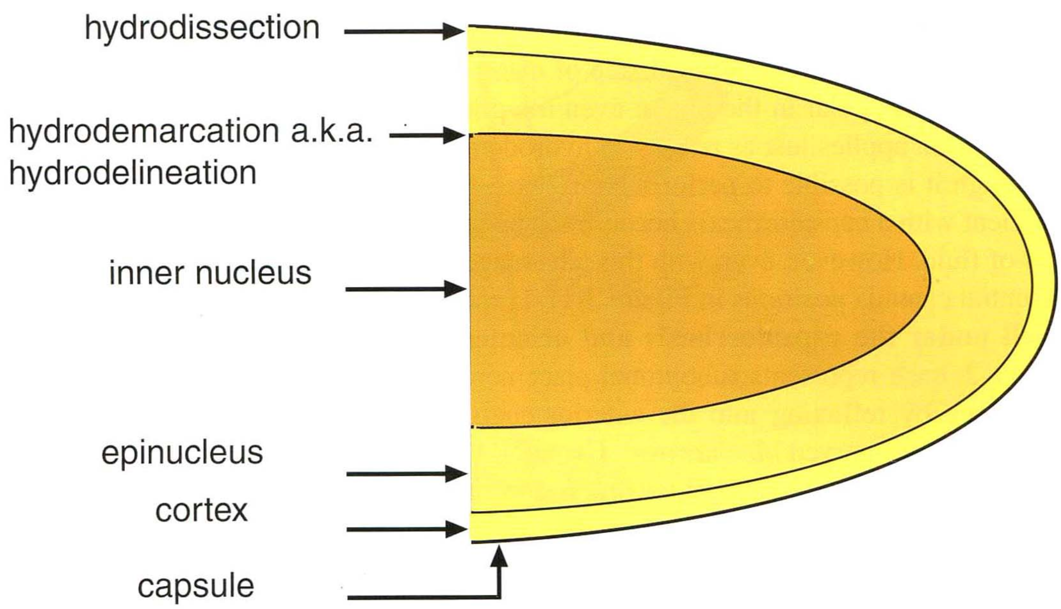

hydrodissection
hydrodemarcation a.k.a.
hydrodelineation
inner nucleus
epinucleus
cortex
capsule

FIGURE 3-10

Hydrodissection Fluid Dynamics

This technique utilizes a pressurized fluid wave (usually from an irrigating syringe and a 27-gauge cannula) to disrupt the adhesions between the capsule and cortex as illustrated in Figure 3-10. Once the initial adhesion is overcome and a dissection plane is established, hydrodissection requires less pressure on the syringe because of the inertia of the advancing fluid wave; therefore, try to complete the procedure in one step with steady pressure on the syringe as opposed to intermittent pulses which will require increased starting pressure each time to reestablish fluid wave inertia. Use just enough pressure to maintain this inertia. Less pressure would not accomplish the goal of a steady convex fluid wave passing across the posterior surface of the lens (Figure 3-11-1). More pressure might compromise the posterior capsule or abruptly eject the nucleus into the anterior chamber. Although this latter result is advantageous for surgeons using the Phaco Flip method, it would require an additional step of using viscoelastic to replace the lens in the bag to facilitate the more popular in-the-bag or even iris plane techniques. This principle of maintaining fluid wave inertia applies just as readily to hydrodemarcation as it does to hydrodissection.

Although it is possible to perform hydrodissection with a can-opener capsulotomy, it is far more efficient with a capsulorrhexis because the intact capsular edge provides a good seal against backflow of fluid. However, even with this advantage, **cannula placement** is important. Note the three potential cannula positions in Figure 3-11-1; each one represents good placement in that **the tip is well under the capsulorrhexis and oriented perpendicular to its edge**. Now look at Figure 3-11-2; each represents suboptimal placement which allows the fluid to follow a path of least resistance by refluxing into the anterior chamber instead of proceeding posteriorly with hydrodissection (see curved blue arrows). Cannula A is not placed far enough under the lip of the capsulorrhexis. Cannula B is almost tangent to the capsulorrhexis edge rather than perpendicular. Cannula C combines both bad aspects of cannulas A and B. Furthermore, the off-axis cannula positioning in Figure 3-11-2 (B and C) is more likely to allow the nucleus to inadvertently pivot anteriorly around them, as opposed to the central positioning of the cannulas in Figure 3-11-1, which tends to hold the nucleus in place during hydrodissection or hydrodelineation. Although these principles of fluid dynamics and optimal cannula placement are described above for hydrodissection, they will also facilitate efficient hydrodemarcation.

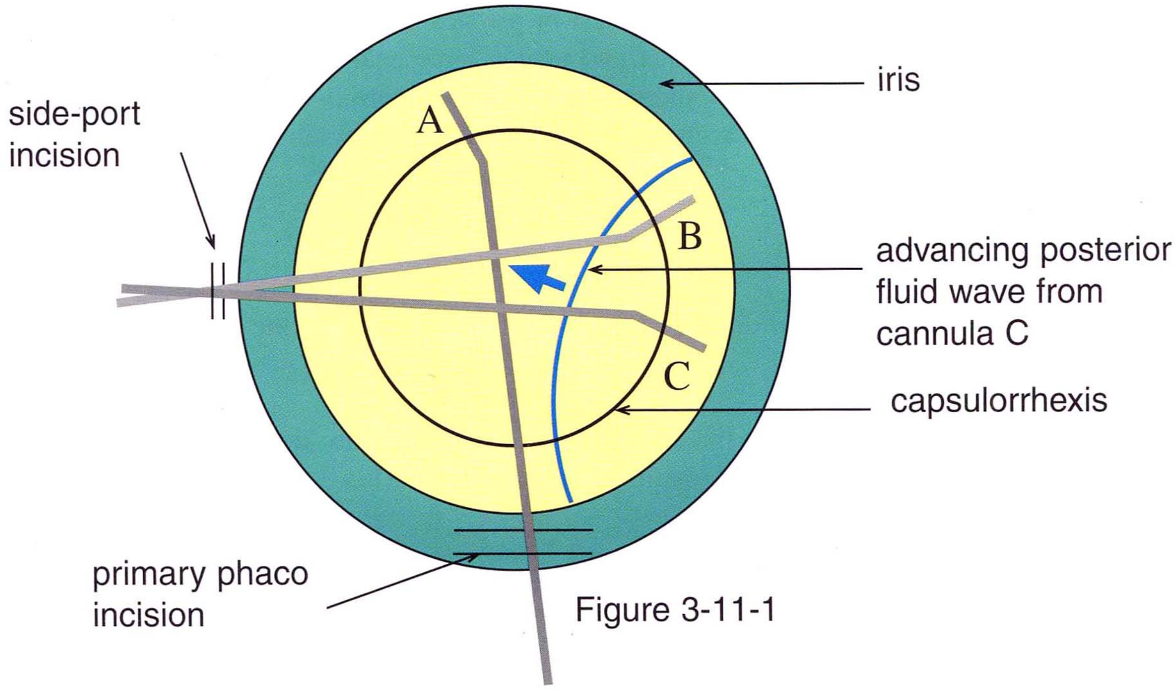


Figure 3-11-1

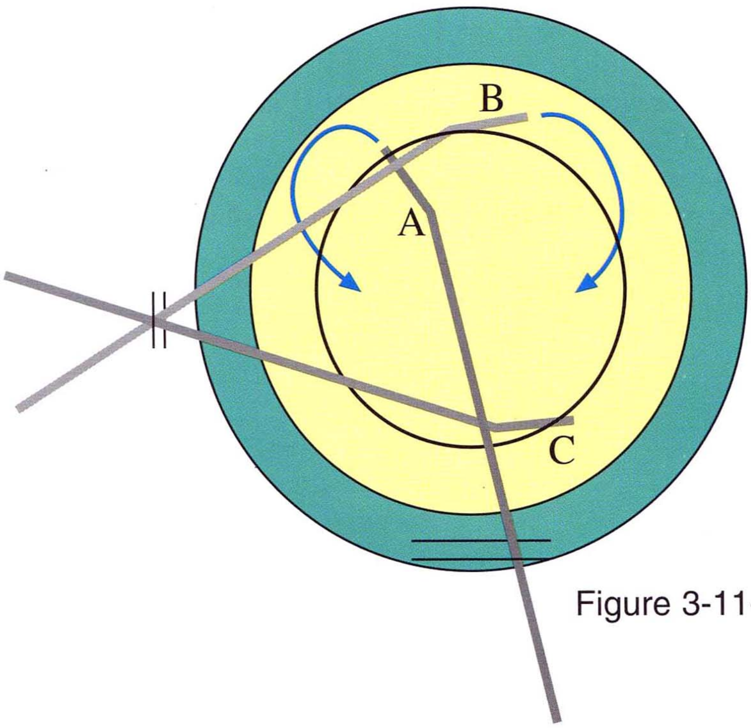


Figure 3-11-2

FIGURE 3-11

Nuclear Rotation: Torque Principles

I know you thought you had seen the last of physics when you finished the MCAT®, but applying a few basic principles of torque and vector force analysis will greatly augment your understanding of many fundamental surgical techniques. Figure 3-12 depicts a nucleus with a groove carved from 6 to 12 o'clock; in order to most efficiently rotate it, we have to review the definition of torque:

torque = force x lever arm

where the lever arm is the distance from the axis of rotation to the point at which turning force is applied.

A force applied at point A, as indicated by the red vector arrow, does not produce any torque because its distance from the axis of rotation (central green dot) is 0.

torque = force • lever arm = force • 0 = 0

A force applied at point B or C produces twice as much torque it would were it applied at point D.

torque (B or C) = force • 2y = 2(force • y)
torque (D) = force • 1y = 1(force • y)

Conversely, twice as much force would be needed at point D in order to produce the same torque as a given force at point B or C.

Clinical corollary: When a certain amount of torque is necessary to rotate a nucleus, it is safest and most efficient to achieve this torque with the longest possible lever arm and correspondingly least applied intraocular force.

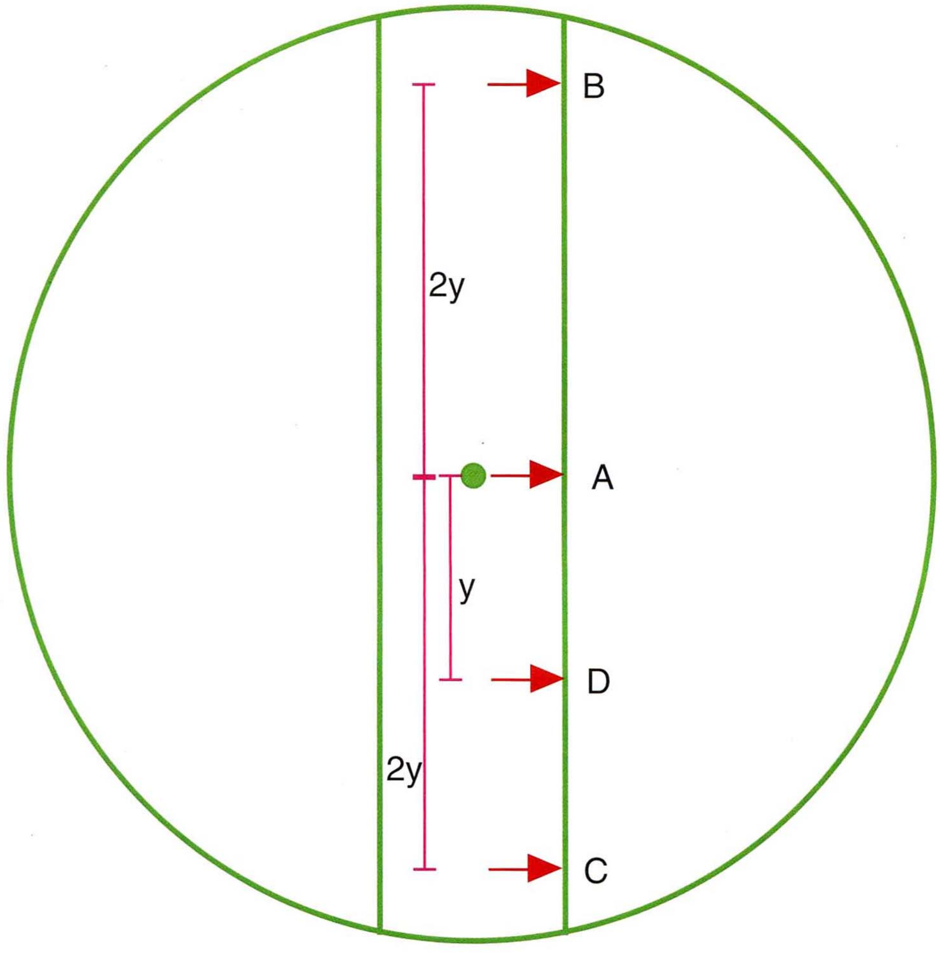


FIGURE 3-12

Nuclear Rotation: Clinical Application of Torque

There are several reasons why the initial groove in a quadrant/divide procedure is longer (more peripheral) at the contra-incisional position than at the sub-incisional position. One reason concerns the phaco needle angle of attack as discussed earlier in this section (see Figure 3-1). Another reason is illustrated in the side views of Figures 3-13-1 and 3-13-2; note that even with the grossly exaggerated phaco handpiece positioning shown in Figure 3-13-2, it is still impossible to sculpt as peripherally sub-incisionally relative to contra-incisionally. The nucleus may need to be rotated 180° in order to complete this groove prior to making the first nuclear crack. Figure 3-13-3 shows the top view of a nucleus manipulation instrument inserted through a side-port incision. The nucleus can be rotated either clockwise if the instrument is pushed against point A, or counterclockwise with the spatula pushing against point B. By applying the torque schematic in Figure 3-12, it can be seen that a given force will produce twice as much torque at point A relative to point B; therefore the best mechanical advantage can be achieved in this situation with clockwise rotation as illustrated in Figure 3-13-4. Note the pivoting of the spatula around the side-port incision so as to avoid wound distortion (see Figures 3-40 and 3-41).

Soft to medium density nuclei especially benefit from the above concept for two reasons. First, the cortex is more adhesive in these cases and consequently tends to resist initial nuclear rotation sometimes even after hydrodissection. Second, an instrument can push against a soft to medium density nucleus only up to a certain amount of force, past which the instrument will start to penetrate the nucleus without applying any further pushing force (see Figure 3-16). Multiplying this maximum possible force by the longest possible lever arm produces the maximum potential torque, whereas trying to obtain this same torque with a shorter lever arm would result in the instrument penetrating the nucleus, and possibly the capsule!

Each particular nucleus requires a certain amount of torque for rotation. Use the above principles to most efficiently apply this torque with the least possible intraocular force; using more force or torque than necessary decreases your safety margin without any compensatory benefit.

Figure 3-13-1

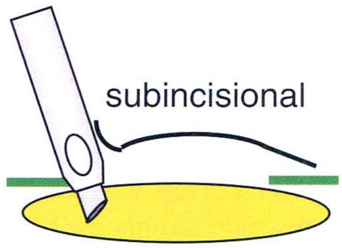


Figure 3-13-2

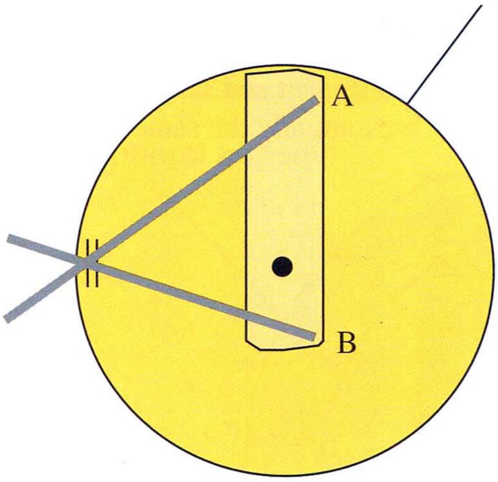


Figure 3-13-3

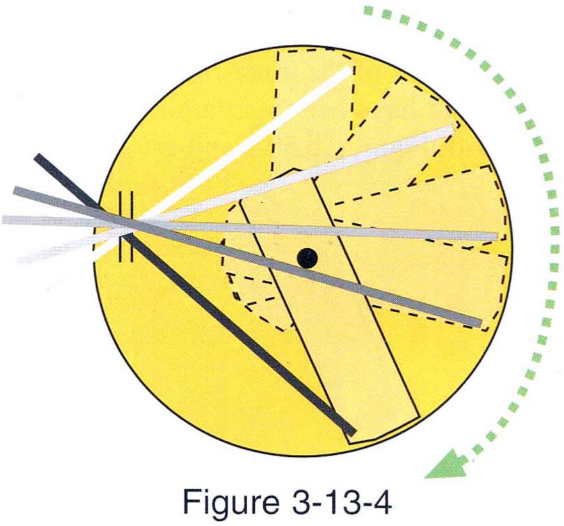


Figure 3-13-4

FIGURE 3-13

Rotating Nucleus: Pulling with Phaco Tip

As discussed several times in Section One, the phaco tip's aspiration port must first be completely occluded in order to obtain a vacuum seal before the occluding material can be manipulated (ie, rotated or centrally mobilized). An important consideration with this technique is the angle of the phaco needle bevel relative to the surface to be occluded (see Figures 1-59A and 1-59B). Figure 3-14 shows a nuclear bowl (ie, after central sculpting as in a one-handed method) which needs to be rotated, although these principles apply equally well to manipulating nuclear halves and quadrants as well as a thick epinuclear bowl. Tip A is not completely embedded into the inner wall of the nuclear rim. Because the aspiration port is exposed to the anterior chamber where indicated by arrow x, vacuum cannot build adequately (see Figures 1-11, 1-29, and 1-30); pulling the tip would simply pull the tip out of the rim rather than rotating or pulling the nuclear rim.

Maintaining the same tip orientation, but placed slightly to the left of tip A's position, tip B completely embeds the aspiration port within the nuclear rim. With this occlusion, vacuum can build and the phaco tip can be used as a handle to manipulate the attached nuclear bowl. Note that tip C is also completely embedded into the nuclear rim; however, the tip of the phaco needle is dangerously close to the nuclear periphery and capsule (see arrow z); furthermore, the vacuum seal is marginal because of the proximity of the aspiration port to the anterior chamber fluid at arrow y (see A-1 and A-2 in Figure 3-31). By rotating the tip 180° so that the bevel would be parallel to the surface of the inner rim at this position, a more efficient and safer complete occlusion like tip B could have been accomplished; this principle is essentially the same as that which was discussed with Figures 1-59A and 1-59B.

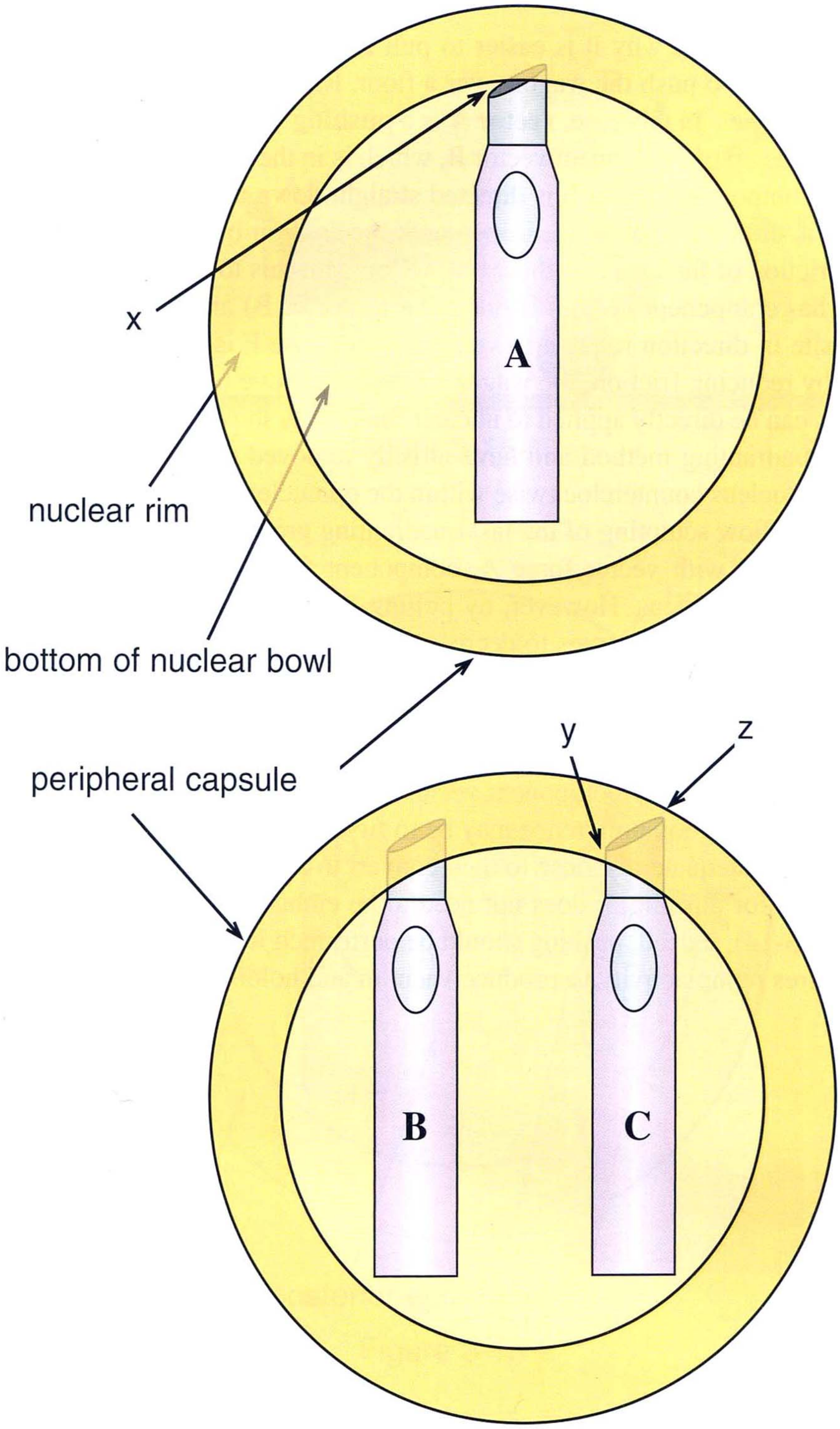

x
A
nuclear rim
bottom of nuclear bowl
peripheral capsule
y
z
B
C

FIGURE 3-14

Rotating Nucleus: Effects of Friction

Figure 3-15-1 demonstrates why it is easier to pull a wagon rather than to push it. Vector force A is applied as shown to push the wagon over a floor. Recall that vectors are comprised of their component vector forces. In this case, **vector A** is a **pushing force** that is directed downward at a 45° angle and is made up of component vector B, which is in the direction of pushing and parallel to the floor, and component C, which is directed straight down against and perpendicular to the floor. Because C is directed downward, it increases the friction between the wagon and the floor as well as the friction of the axles on the wheels. Compare this to the **pulling force** exerted by **vector D**, which has component vectors E (identical to vector B) and component F (equal in magnitude but opposite in direction relative to vector C). Because F is decreasing the weight of the wagon and thereby reducing friction, the wagon is easier to move by pulling.

These principles can be directly applied to nuclear rotation as shown in Figure 3-15-2. In this case we are using a quadranting method and have already removed the first two quadrants. We now want to rotate the nucleus counterclockwise within the epinuclear bowl so that its flat surface will face the surgeon to allow sculpting of the last quadranting groove. If phaco needle Y is used to push the nucleus around with vector force A, component force C will increase the friction between the nucleus and epinucleus. However, by pulling the nucleus with phaco needle X and vector force D, component vector F serves to decrease friction and facilitate rotation. Vacuum is used as a gripping force for pulling with the tip occlusion optimized as discussed in Figure 3-14. Taking friction into account is especially important with softer nuclei which have stickier adhesions between nucleus, epinucleus, and cortex; this can be true even after hydrodissection and hydrodemarcation. Note that rotating component vectors E and B are equivalent.

Of course, individual surgeon preference may be to first attempt pushing as described above and only in the event of inadequate response to then convert to a pulling method. Note that when the phaco needle is used for pushing, it does not need to be embedded completely as is the case for pulling (see Figure 3-14); indeed, pushing should be performed in pedal position 1 as opposed to pulling which requires pump activity to produce vacuum and holding force (position 2).

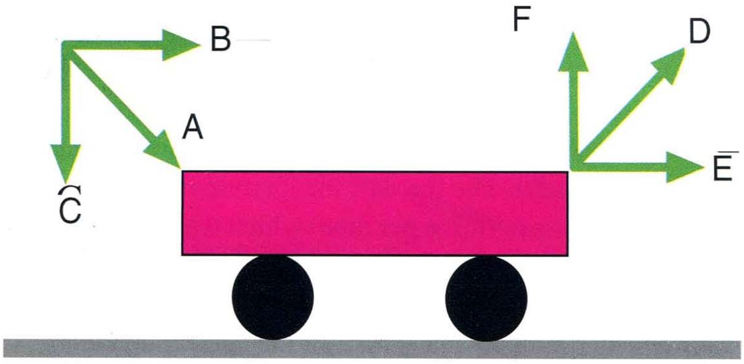


Figure 3-15-1

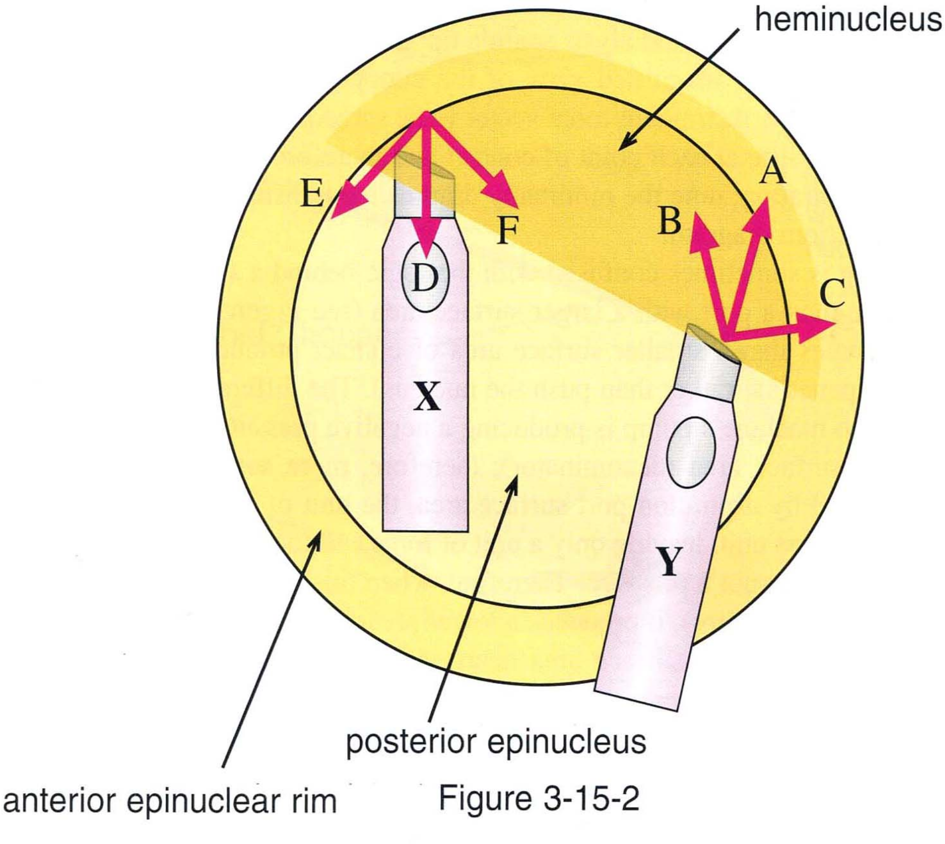


Figure 3-15-2

FIGURE 3-15

Optimal Instrument Placement for Nuclear Manipulation

When attempting to manipulate the nucleus (ie, rotation, cracking, etc), both the shape and the placement of the manipulating instrument are important. In Figure 3-16, each instrument is pushed against the nucleus with the same amount of force (large green vector arrow). It can be seen that the effectiveness with which this force is transferred to the nucleus varies. For example, a cyclodialysis spatula has a small frontal surface area (essentially the same as the cross-sectional surface area of the instrument shaft). The force of the instrument applied over this small surface area produces a relatively high pressure (force per area) which tends to penetrate the nucleus rather than transferring the instrument's pushing force; note the significant nuclear penetration and small transmitted force vector of cyclodialysis spatula A. Cyclodialysis spatula B has less penetration and more transmitted force because of its placement in the central densest nucleus as opposed to the less dense epinuclear placement of instrument A.

The Seibel Nucleus Chopper was developed with these phacodynamic principles in mind to serve not only as a chopper but also as a universal nuclear manipulator. The distal curve allows optimal placement of the instrument tip into a posterior groove for the greatest mechanical advantage when cracking (Figure 3-18-1). Furthermore, the distal tip is a polished olive shape which has a much larger surface area than the cyclodialysis spatula tip; note the greater area of contact indicated by more blue arrows in the magnified view of the chopper relative to the spatula. This expanded surface area allows the instrument force vector to be spread out over a larger area of the nucleus, resulting in less pressure at each point of contact and therefore more effective transmission of force with less penetration; note the minimally diminished transmitted nuclear force vector (green arrow) in the bottom diagram.

The above reasoning is sometimes confused with the logic behind a smaller aspiration port having less holding force than a port with a larger surface area (see Figure 1-60). However, the instrument shape logic states that a smaller surface area of contact produces a higher pressure (which is more likely to penetrate rather than push the nucleus). The difference between the two rationales is that the phaco machine's pump is producing a negative pressure, which has the units of force (numerator) per surface area (denominator); therefore, more surface area yields more force (pressure is multiplied by aspiration port surface area, the unit of which cancels the pressure's denominator surface area unit, leaving only a unit of force). In the instrument diagrams, the instrument has an applied force, not a pressure. Therefore, when this force is applied over a larger surface area (ie, larger denominator), it produces a lower pressure with units of force over surface area, with the pressure per unit surface area decreasing as the total applied surface area (denominator) increases. (See also Appendix B.)

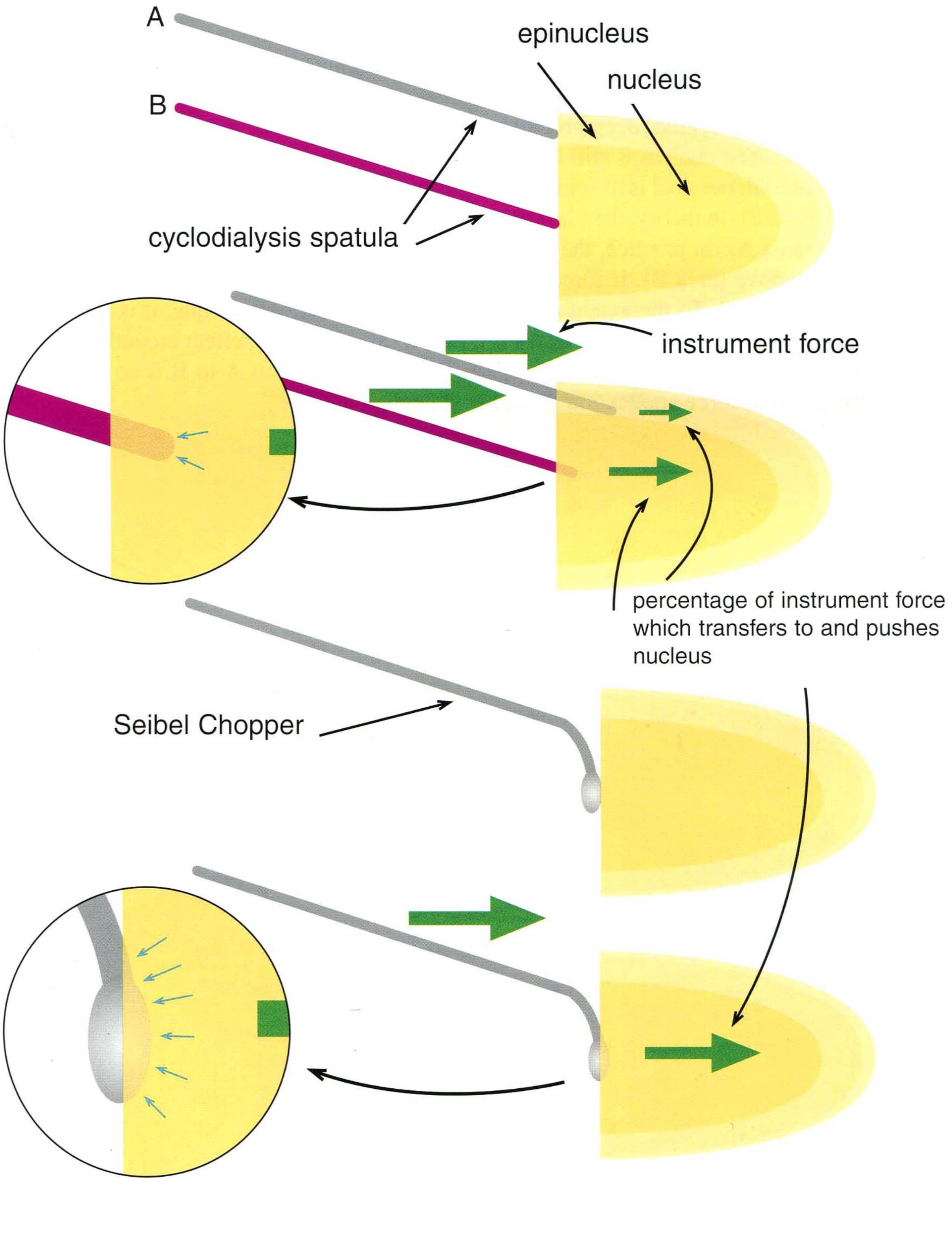

A
B
epinucleus
nucleus
cyclodialysis spatula
instrument force
percentage of instrument force which transfers to and pushes nucleus
Seibel Chopper

FIGURE 3-16

Nuclear Segmentation 1

As discussed in Figure 3-16, instrument placement is important with regard to effective transmission of force from the instrument to the cataract. There is additional logic behind instrument placement when performing cracking maneuvers. Figure 3-17 shows a cross-section of a nucleus with a well-prepared, deep groove as an initial step in either a stop and chop or a quadranting maneuver. The nucleus is still connected at the bottom of the groove by a bridge of posterior nuclear material; our goal is to split the nucleus into two halves (the following principles apply to quadrants as well). In theory, the ideal place to apply the splitting force would be in the middle of the bridge (area A). In practice, the same effect can be approximated by applying force at the bottom of the groove (area B). If force is applied as shown at area C, a torque is created with a lever arm from A to C. To the extent that the force is converted into torque, it is not effectively applied at the bridge to split it apart. Instead, it will create a pivoting effect around the most posterior aspect of area A without pulling it apart. The lever arm from A to B is so short that any induced torque from force application at area B is negligible.

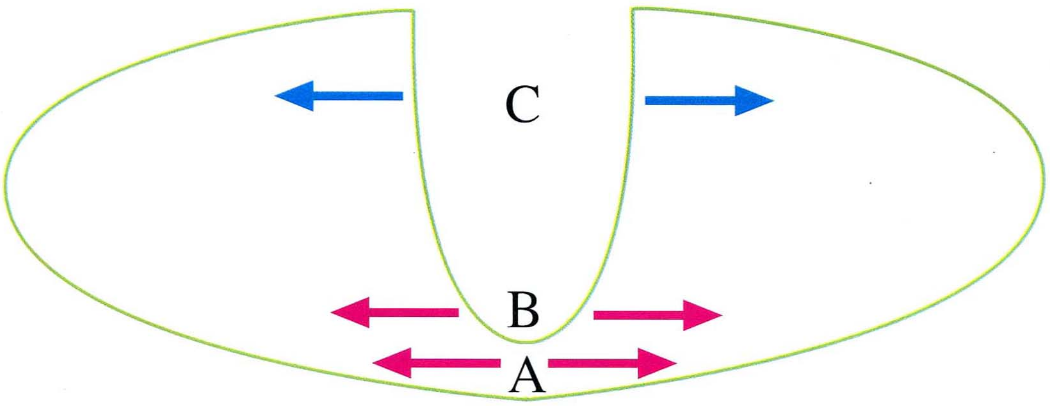


FIGURE 3-17

Nuclear Segmentation 2

Figure 3-18-1 shows instruments well placed at the bottom of the groove. The phaco needle can easily be positioned posteriorly in the groove because it is oriented parallel to the groove. Because the second instrument is perpendicular to the groove, it is useful for it to have a curve such that the distal tip can also be placed down in the groove as shown by the Seibel Chopper illustrated here. The nucleus is bisected with a minimum of instrument and nuclear movement. Note also that the force has been effectively applied at the bridging tissue such that the split faces are parallel (ie, they were split directly apart).

Figure 3-18-2 has instruments placed in a poor position anteriorly in the groove. The nucleus is pushed apart much further than in Figure 3-18-1, yet the top portion of the posterior bridge is only split apart the same amount. Moreover, the bottom of the bridge is not split at all because the anterior placement of the instruments has created a torque in this area rather than a splitting force.

If posteriorly placed instruments penetrate the nucleus instead of pushing it apart, try moving them slightly anteriorly toward the central densest part of the nucleus (ie, still in the posterior half of the nuclear face; see Figures 3-10 and 3-16).

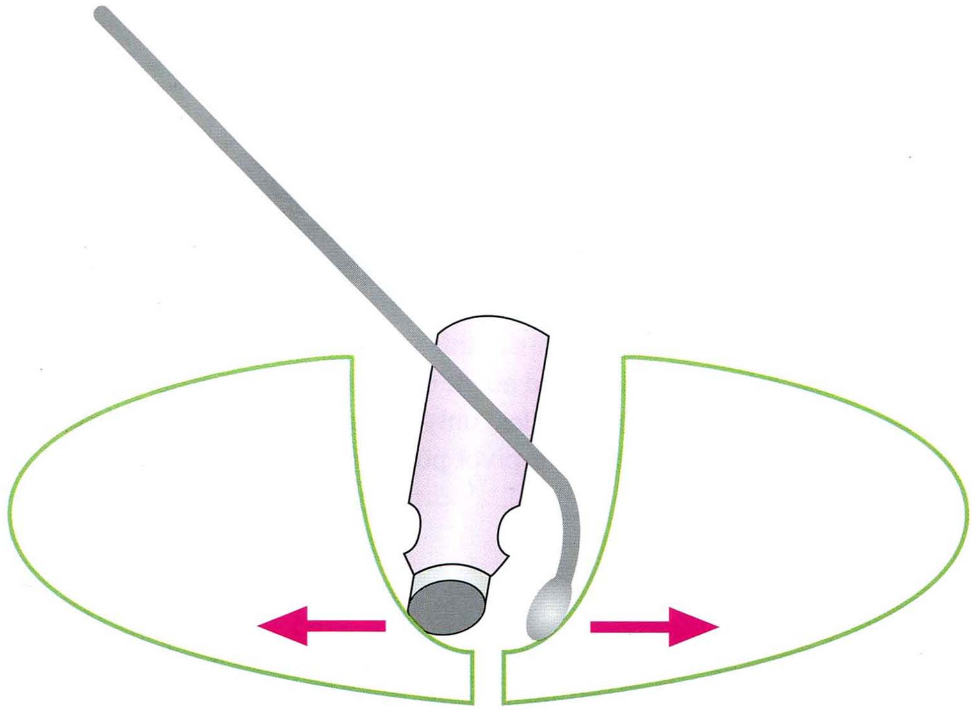


Figure 3-18-1

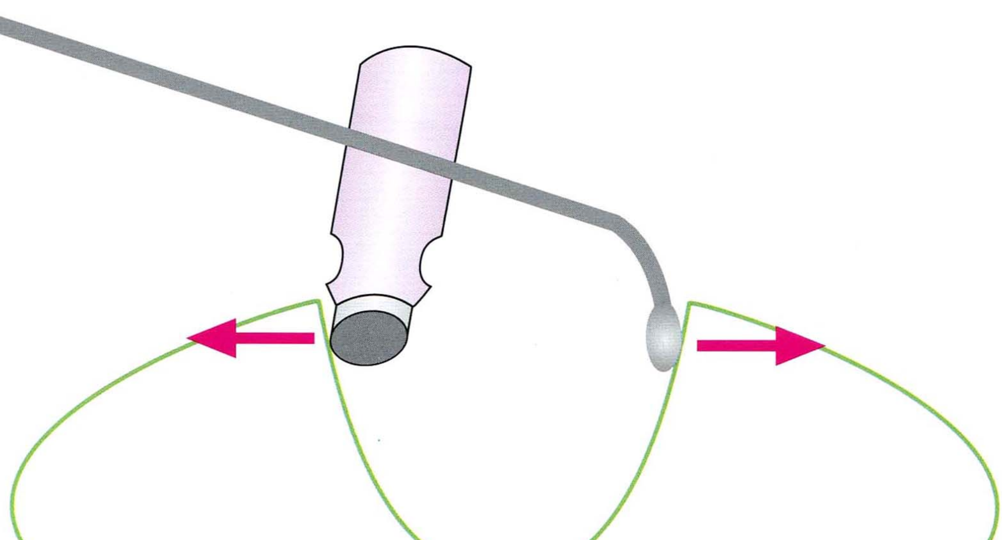


Figure 3-18-2

FIGURE 3-18

Nuclear Segmentation 3

Figure 3-19 superimposes the effects of anterior instrument placement (green) and posterior instrument placement (red). The separation distance necessary to break apart the bridge of connecting nucleus at the base of the groove is represented by x. Note that each nuclear half moves only half this amount (1/2 x) with posterior instrument placement, thus imparting minimal stress to the surrounding intraocular tissues. Compare this to the anterior instrument placement schematic, in which the nuclear halves are displaced about 6 times as much (distance 1/2 y). For all of this unnecessary strain on the capsule and zonules, only the top of the bridge is split adequately, with the bottom remaining intact and acting as a pivot point (see Figure 3-18-2).

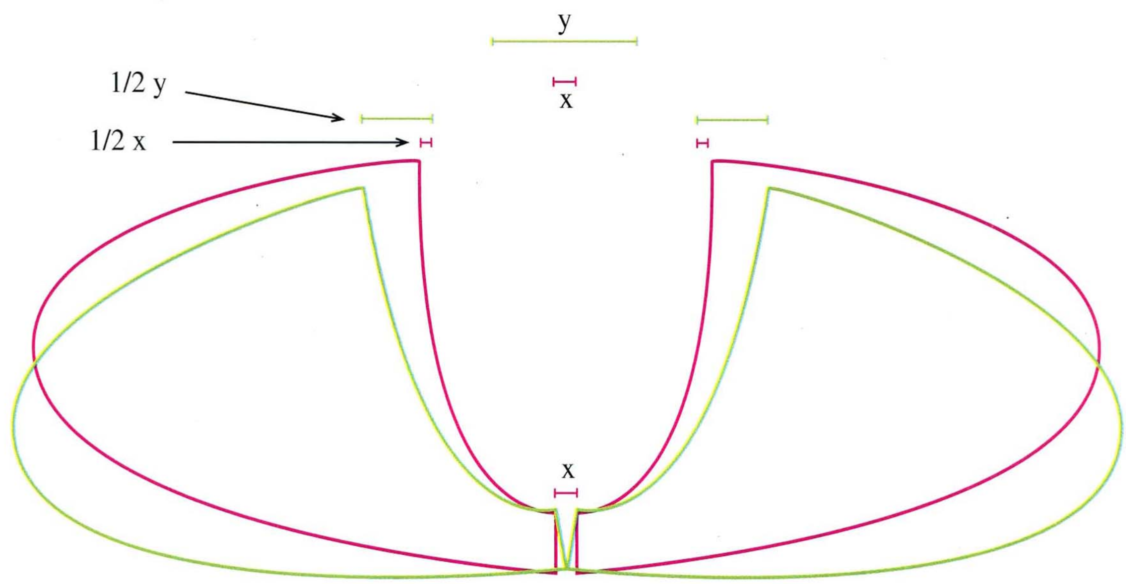


FIGURE 3-19

Nuclear Segmentation 4

In Figure 3-20, the remaining nuclear half has been grooved and almost completely quadranted by using the splitting methods previously discussed. However, a small bridge of tissue (A) remains. Options include repeating the previous methods, using viscoelastic with the Salz Nucleus Splitter, or using the instruments as illustrated in Figure 3-20. In this case, the phaco needle is occluded and exerting a pulling force with the foot pedal in position 2. At the same time the Seibel Chopper is inserted through the side-port incision and is used to exert a pushing force. The combination of these forces produces a shearing force across the bridge A, effectively separating the half into quadrants. Since one quadrant is already engaged on the phaco needle, it can readily be mobilized into the center of the posterior chamber or iris plane and emulsified.

Another option in this case would have been to place the Seibel Chopper at the periphery of bridge A in order to perform a chopping maneuver as was illustrated in Figure 2-15.

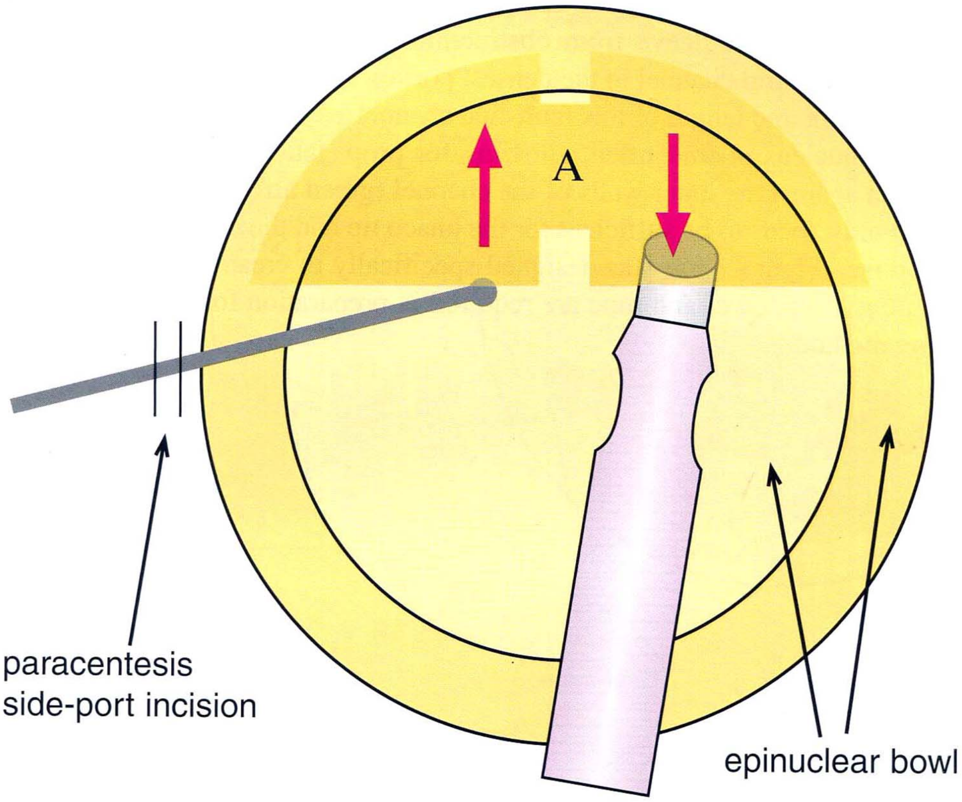


FIGURE 3-20

Fault-Line Phaco

I developed this segmentation technique as an exercise in the application of Phacodynamic principles to both instrument design and surgical methodology. The development began with a mechanical analysis of the human crystalline lens, which is an oblate spheroid of increasing density from the periphery toward the center. Grooving methods of nuclear segmentation use considerable sculpting as they progress from anterior to posterior; the grooves must also be wide enough to prevent the silicone irrigation sleeve from obstructing progress. However, all that is really required for cracking is a central channel in the densest portion of the nucleus. Figures 3-21-1 and 3-21-2 show that the height and length of this fault-line channel are such that a significant amount of the central densest nucleus is emulsified, allowing for propagation of cracking (red arrows) when force is directed against the inner walls of the channel (green arrows). Toward this end, the width of the channel only needs to be sufficient for the phaco tip and the cracking instrument. The Flat-Head Phaco tip (see Figure 1-62) was designed specifically to create this channel such that considerably less ultrasound power and time are required in preparation for cracking relative to a traditional grooving method.

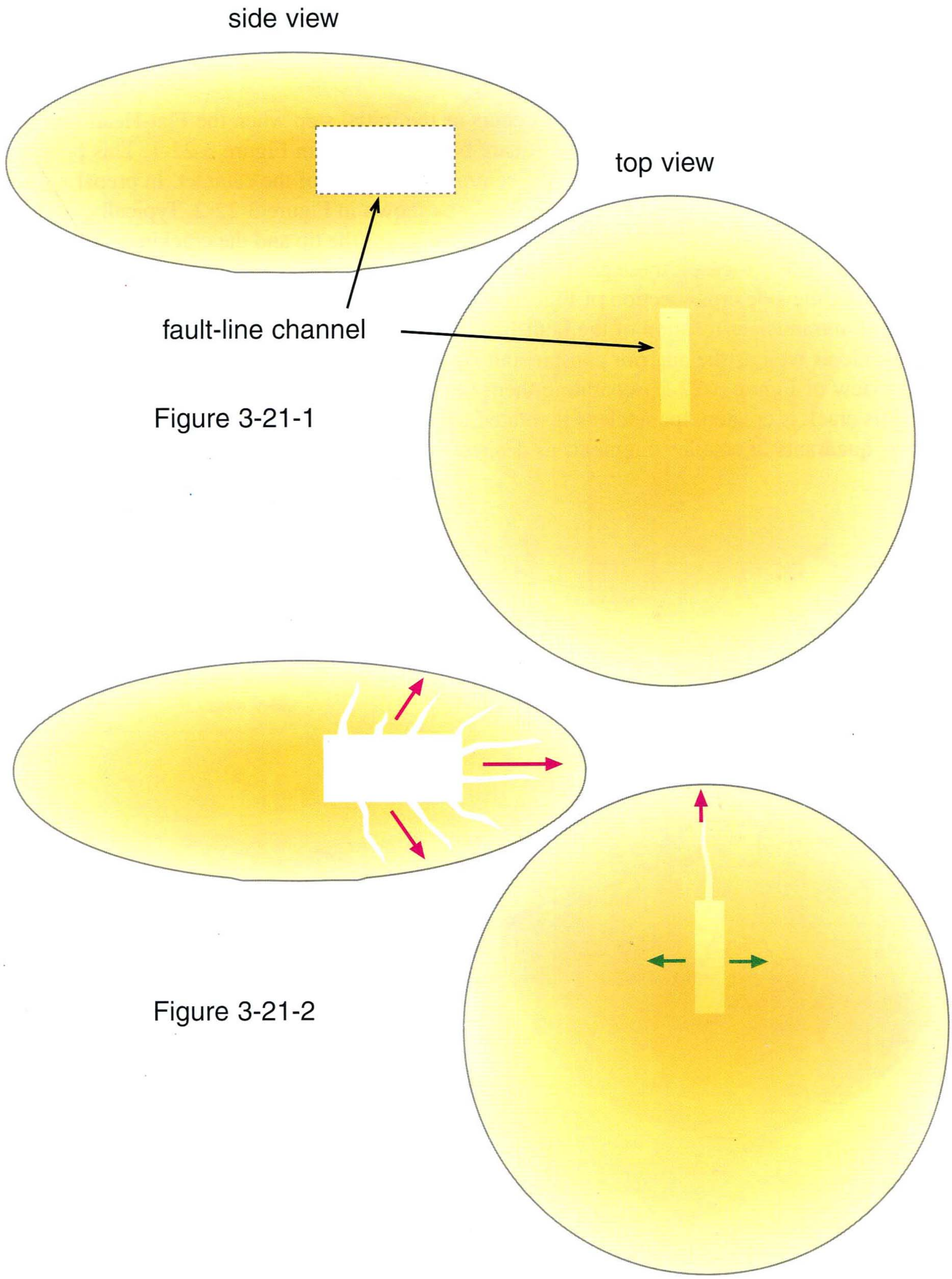

side view
top view
fault-line channel
Figure 3-21-1
Figure 3-21-2

FIGURE 3-21

Fault-Line Phaco (continued)

The only sculpting in this technique occurs as the initial step when the Flat-Head Phaco tip is oriented horizontally to create a small square bowl as shown in Figure 3-22-1. This bowl will allow the fault-line channels to begin in the central densest part of the cataract. In preparation for creating the channels, the tip is oriented vertically as shown in Figure 3-22-2. Typically, only two side-by-side passes are required to provide enough room for the tip and the cracking instrument (a Seibel Chopper in this case); these passes are made with efficient occlusion mode phaco. Note the green bars in the side cross-section of Figure 3-22-2; these indicate the safety margin afforded by the central intranuclear location of the fault-line channel with respect to the posterior and peripheral capsule as well as the anterior capsule and iris. With the instruments positioned as shown in the top view of Figure 3-22-2, separating them will produce a crack as shown in Figure 3-21-2. Once this crack is created, the nucleus is rotated to facilitate more fault-line channels and cracks, creating quadrants or smaller fragments as desired.

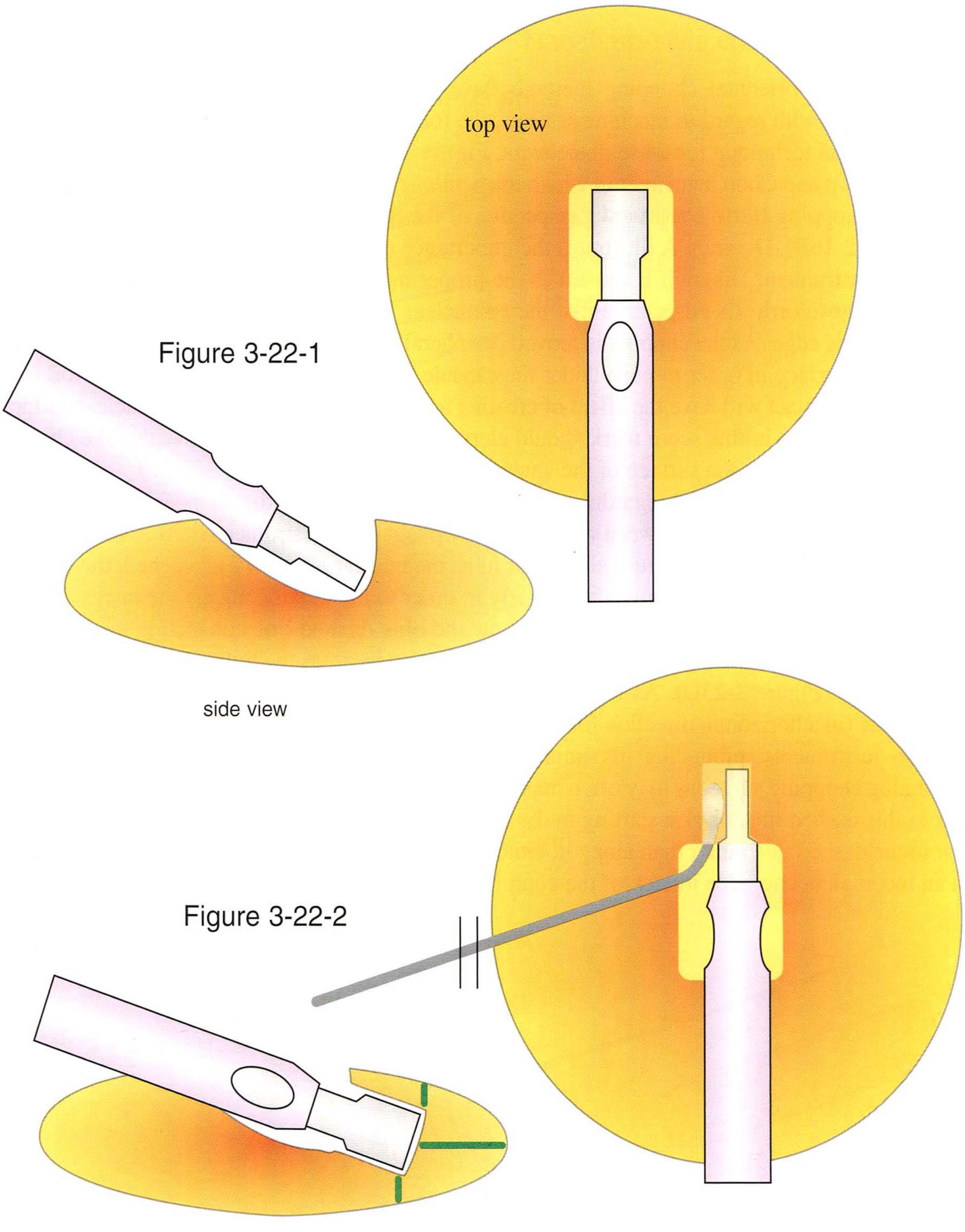


FIGURE 3-22

Horizontal Chopping Techniques 1

Although horizontal chopping methods have been previously discussed in Figures 2-14 through 2-16B with regard to machine settings, the following discussions will focus on optimization of surgical technique for these maneuvers. **Figure 3-23** shows multiple **side view cross-sections** of a Stop and Chop maneuver in which the heminucleus is impaled by the phaco tip in preparation for chopping (for the top view perspective of the Stop and Chop maneuver, see Figures 2-15 through 2-16B). Diagram A illustrates the importance of avoiding the anterior capsule with the chopping instrument. Diagram B illustrates the proper initial placement of the chopper just central to the capsulorrhexis edge; note that the epinucleus has been removed up to the area of the capsulorrhexis edge. As the chopper is moved peripherally, the tip is kept in contact with the anterior nuclear surface in order to push under the capsule rather than accidentally jump on top of it; this constant contact will have the effect of creating a gentle **scoring mark** on the nuclear surface, and an interruption in this score mark should alert the surgeon to the possibility that the chopper may have slipped onto the surface of the anterior capsule.

Another important point regarding this peripheral movement of the chopper is its temporary rotation such that the angle between the chopping tip and main instrument shaft is more parallel with the iris plane in order to better slip under it; as the nuclear periphery is reached, the chopper tip is rotated back such that it points posteriorly in order to maximally engage the nucleus (green curved arrows in Figure 3-23C and D). Note how the **blue dashed line** connecting the bottom of the chopping tip with the bottom of the phaco needle encompasses the bulk of the nucleus anterior to the line (Figure 3-23D). As the chopper tip is then drawn toward the phaco tip along this dashed line (in a horizontal direction for horizontal chopping), the nucleus is compressed between the two instruments, producing maximum efficiency in propagating the chop's fracture line. Beginning chopping surgeons may often make the mistake of having one or both instruments anterior to this dashed line, or else starting in the correct position but then drawing the chopper anterior to the dashed line rather than along it; either of these incorrect maneuvers will typically result in an incomplete chop due to lack of the compressive effect as described above.

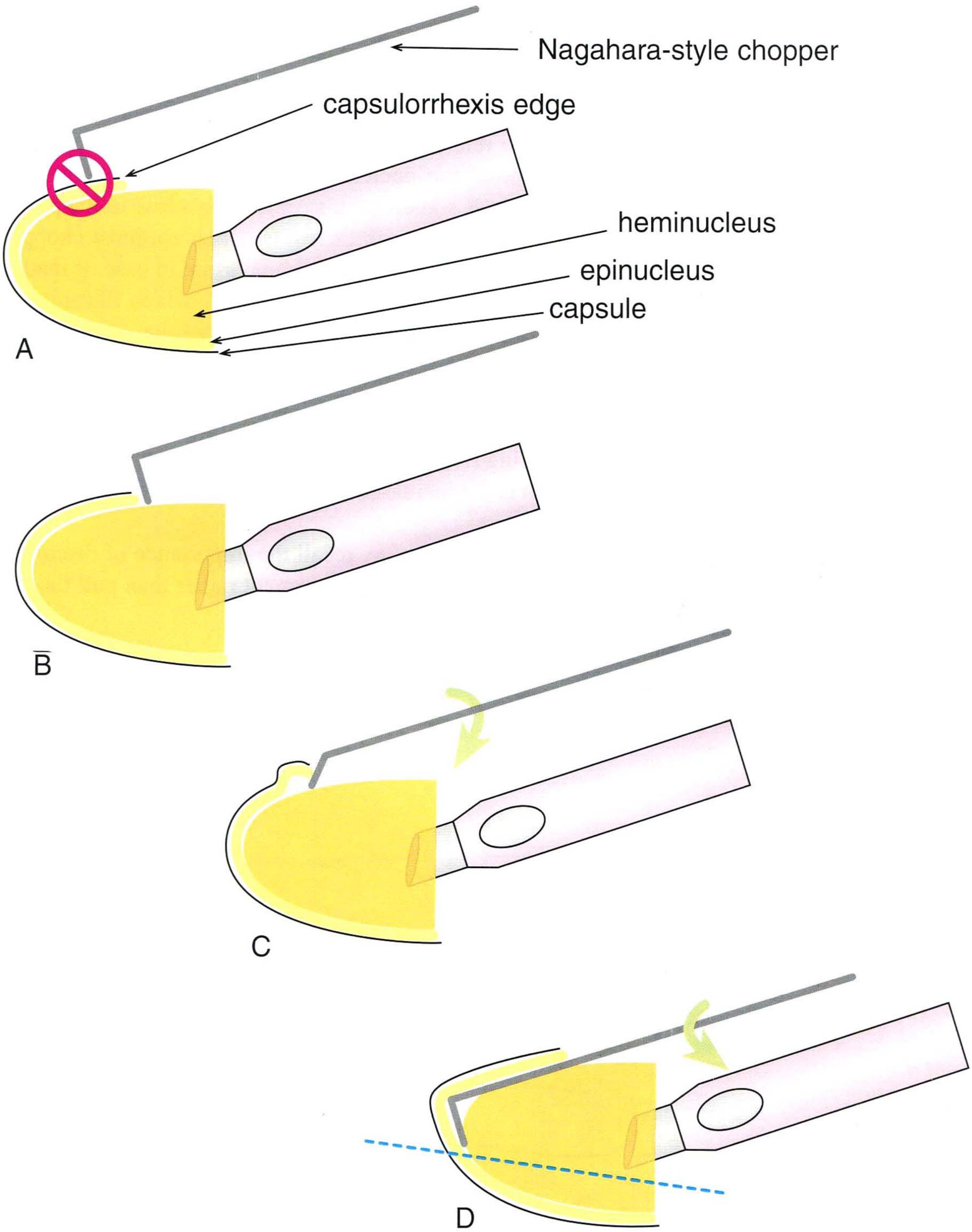

Nagahara-style chopper
capsulorrhexis edge
heminucleus
epinucleus
capsule
A
B
C
D

FIGURE 3-23

Horizontal Chopping Techniques 2

Although Figure 3-23 illustrates proper instrument placement for chopping, it also illustrates some of the reasons behind the slow adoption of this technique by the ophthalmic community. First, it is somewhat challenging to dissect the relatively large chopping tip under the capsulorrhexis and iris in order to reach the endpoint of the nuclear periphery just prior to the chop. Furthermore, it can be seen that the chopping tip is somewhat uncomfortably close to the posterior capsule in this position (Figure 3-23D), and even though the tip is not sharp, most choppers' tips have a small enough surface area to provide uncomfortably high pressure in case of inadvertent contact with the capsule. These liabilities are addressed in Figure 3-24, which illustrates the use of vacuum to grip the heminucleus and pull it away from the periphery (blue arrow) so that the chopper placement is more easily facilitated with less dissection and with better visualization of the peripheral endpoint; this maneuver was independently described by Paul Koch as the Stop and Chop technique and Ron Stasiuk as the Mini-Chop method. Central mobilization of the heminucleus is made possible by initial grooving (ie, debulking) and cracking of the whole nucleus. An additional advantage of these methods is the increased distance and safety margin between the chopper tip and the posterior capsule.

When pulling a fragment impaled by the phaco needle, recall the importance of discontinuing ultrasound; a vibrating needle will typically pull out of the fragment rather than pull the fragment with it.

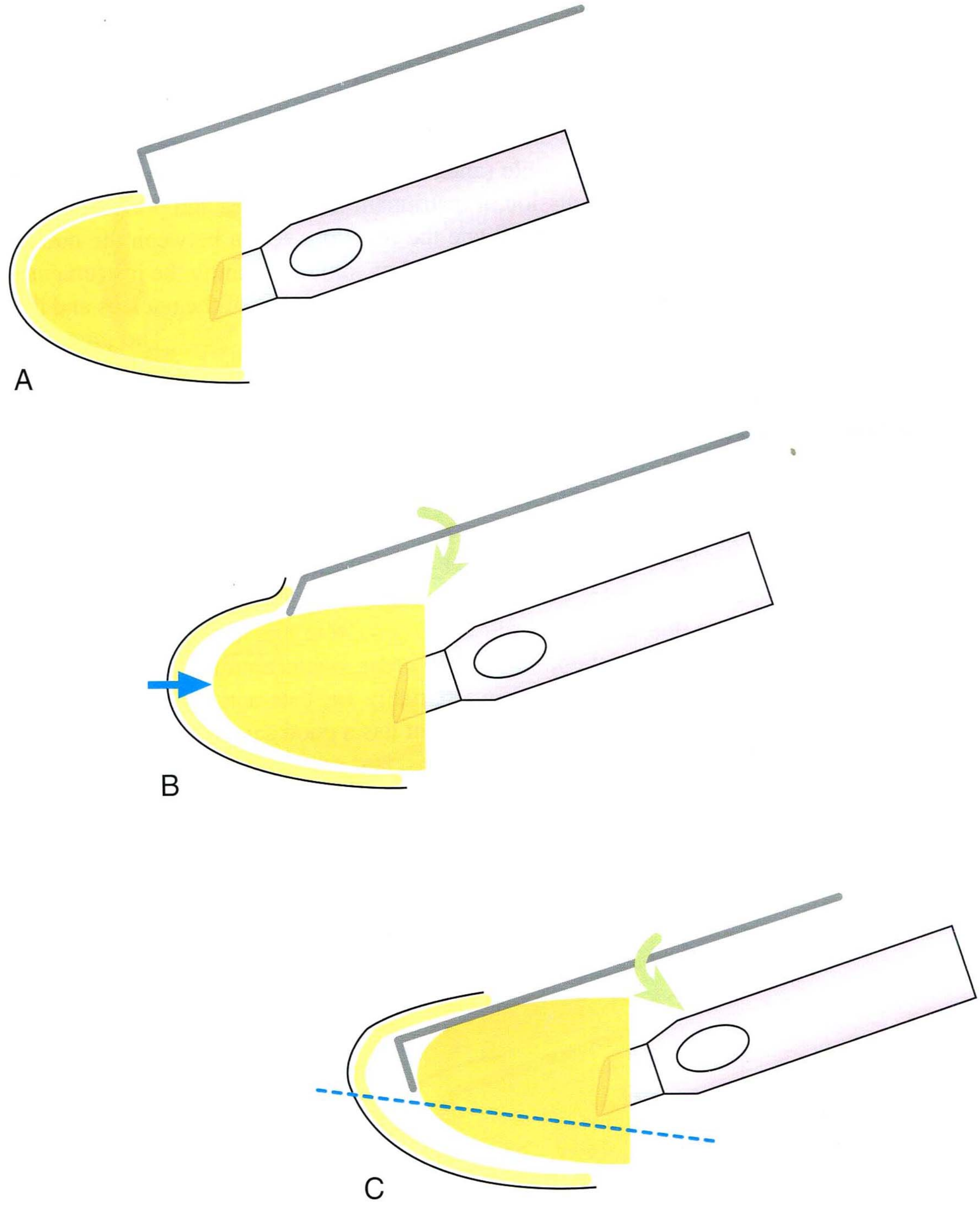


FIGURE 3-24

Horizontal Chopping Techniques 3: Seibel Chopper

The safety and efficacy of the procedure illustrated in Figure 3-24 are further enhanced by the use of the Seibel Chopper as shown in Figure 3-25. The polished distal olive-shaped tip has a much larger surface area than the tips of standard choppers; therefore, the olive tip is much less likely to damage or penetrate the lens capsule (anterior, peripheral, or posterior) in case of inadvertent contact (see Figure 3-16 for discussion of instrument surface area and pressure). The olive tip's shape and larger surface area further facilitate the blunt dissection between the nucleus and epinucleus; nevertheless, the technique is still optimized by initially rotating the instrument so that the plane of the distal bend is closer to the plane of the anterior surface of the nucleus and the anterior capsule (see curved green arrows in diagrams B and C in Figure 3-25). The junction of the olive tip and the curved shaft creates an angle that positively engages the nuclear periphery (red arrow in diagram C, Figure 3-25); this angle helps to maintain engagement during the actual chop. Note also how the curved shaft more anatomically approximates the nuclear periphery (blue arrows in diagram C, Figure 3-25) relative to the abrupt 90° bend of standard choppers (eg, diagram C of Figure 3-24); the gently radiused 105° curve also better facilitates entry and exit through the side-port paracentesis incision relative to standard choppers' abrupt 90° bend.

The chopping edge of the curved shaft is offset 45° to facilitate use as shown in the top (surgeon's) view illustrated in Figure 2-15; note the 45° angle between the straight instrument shaft and the direction of the chop (top diagrams in Figure 3-25). Note that the curved shaft tapers to a very small radius of curvature at the chopping edge in order to concentrate the instrument's force into a pressure (recall Figure 3-16) that will cleave virtually any cataract; however, it is intentionally not sharpened to a knife edge so that the instrument has a good safety margin when using the inner curved segment to manipulate the intraocular lens, iris, paracentesis incision, etc.

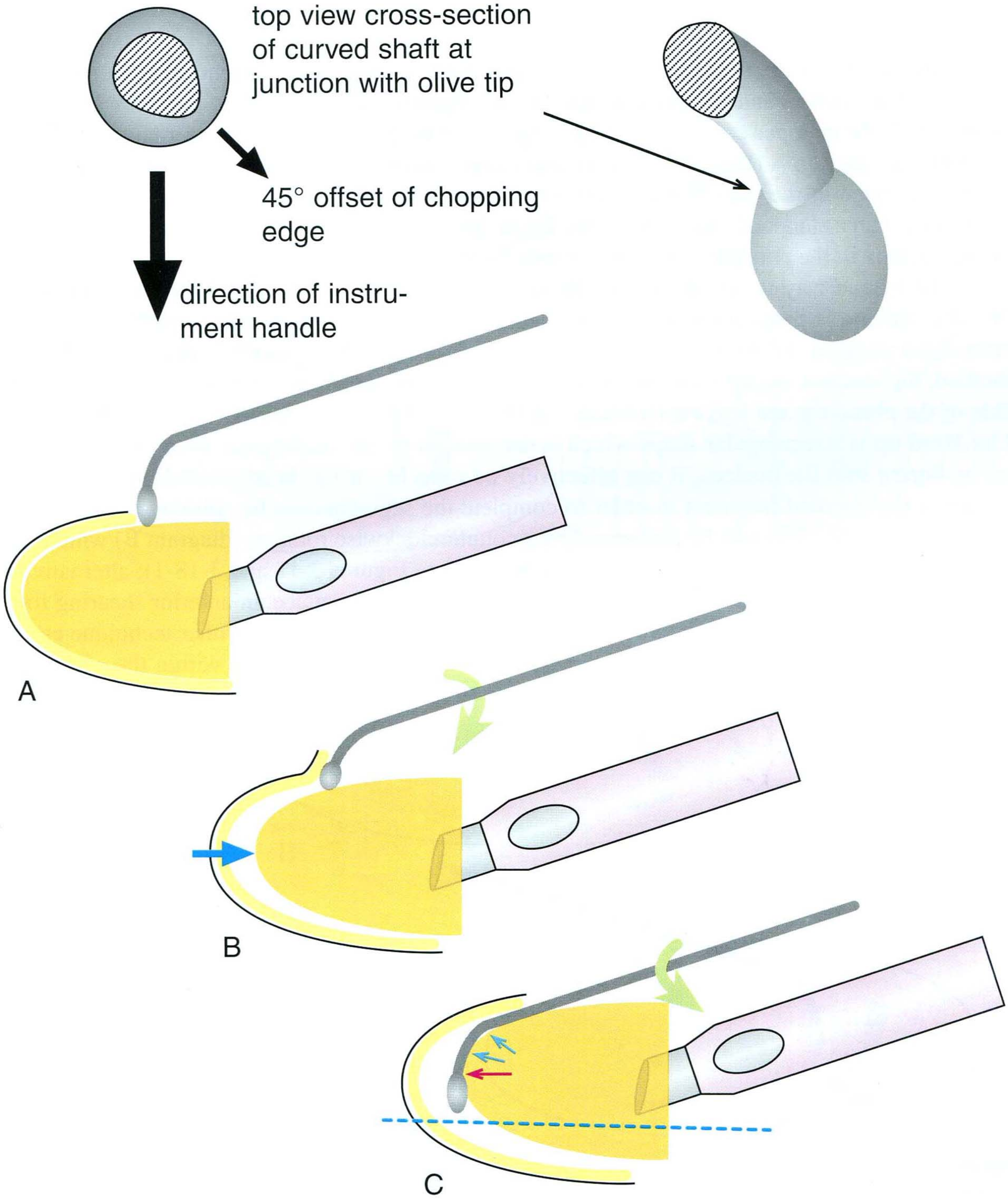

top view cross-section
of curved shaft at
junction with olive tip
45° offset of chopping
edge
direction of instru-
ment handle
A
B
C

FIGURE 3-25

Horizontal Chopping Techniques 4: Flat-Head Phaco Tip

The Flat-Head tip, seen in Figures 1-62 and 3-22, is also useful for chopping in two ways. First, the fault-line channel created when the tip impales the heminucleus provides a cleavage plane which the chopper can meet halfway; this would be the case if the chopper had been placed at point y in diagram A (Figure 3-26) and than drawn toward the tip as indicated by the red arrow. Recall the shape of the fault-line channel (see Figure 3-22-2) which is taller in anterior-posterior dimension than a standard round phaco needle; it therefore eliminates more of this densest portion of the nucleus in the chopping plane and better facilitates a complete chop.

The second way in which the Flat-Head tip may be used is directly illustrated in Figure 3-26. This method is particularly useful with dense fibrous nuclei which may not chop completely such that a posterior bridge of connecting material remains, such as point z in diagram A. For this method, the chopper engages the heminucleus at point x such that the chop will extend just to the side of the phaco tip and leave it embedded in the fragment to be chopped as shown. Because the Flat-Head tip is a rectangular shape which is surrounded by the rectangular shape which it created by boring into the nucleus, it can effectively be used like a flat-head screwdriver to transmit torque to the impaled fragment in order to complete the segmentation by splitting the remaining posterior adhesion. This can be performed by a counterclockwise rotation (diagram B) which produces a splitting force right at the connecting bridge (see Figures 3-17 and 3-18-1); alternatively, a clockwise rotation can be employed (diagram C) which will produce an anterior shearing force at the connecting bridge (see Figure 3-20). Both ways are effective, and neither technique can be effectively used with a standard round needle, which would tend to rotate within the cylindrical hole which it bored rather than transmitting torque to the impaled fragment.

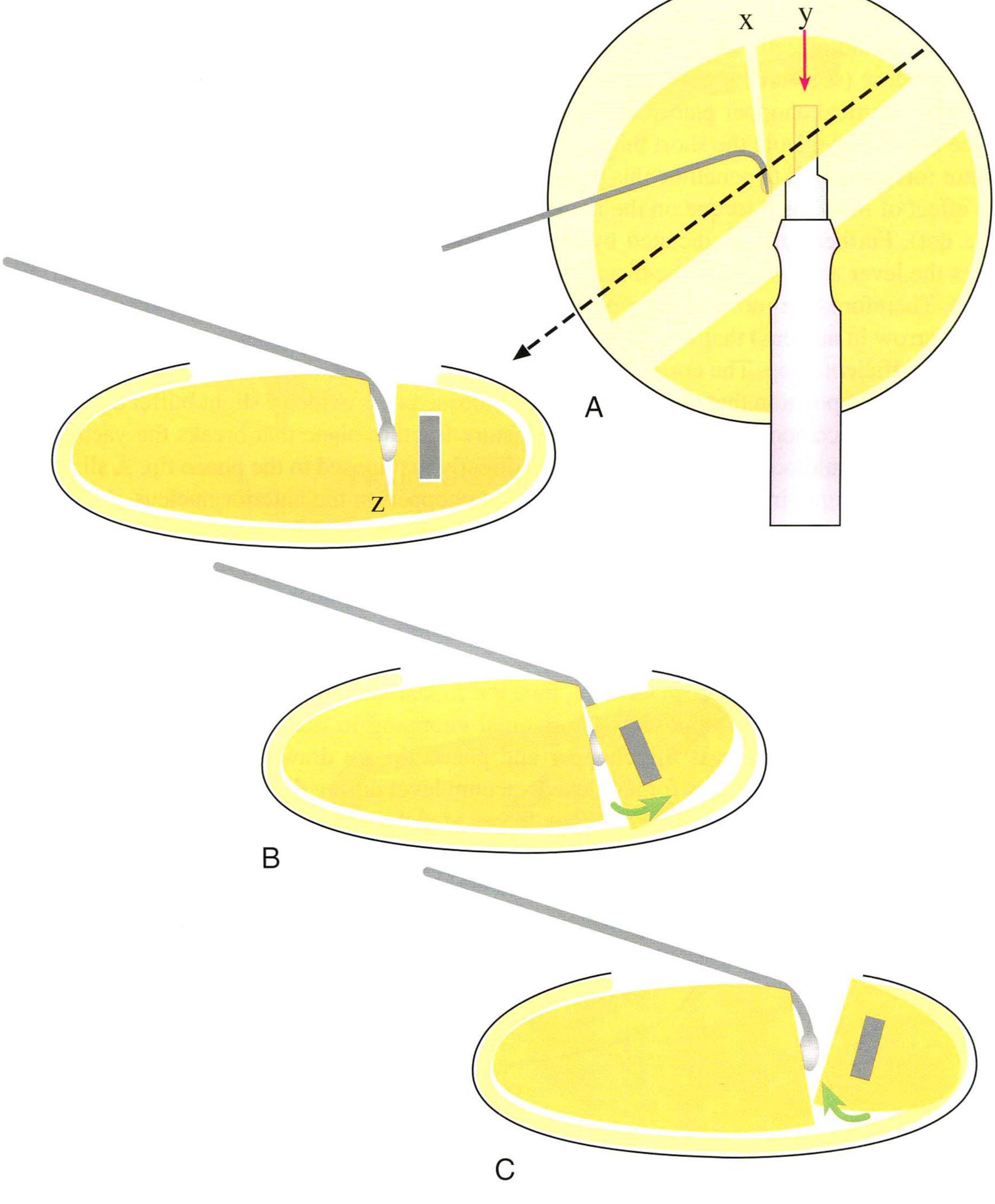


Figure 3-26

Vertical Chopping Techniques

The initial placement of the vertical chopper significantly affects the ease and efficiency of the procedure (see vertical chopping in Figures 2-17 and 2-18). Figure 3-27-1 shows two potential initial vertical chopper placements, one just distal to the phaco tip and one more distal closer to the rhexis edge. Note the short blue arrows superimposed on the chopper tips that represent the vector force required to penetrate this particular nuclear density. However, this force will also have the effect of inducing a torque on the nucleus around the pivot point created by the phaco tip (see blue dot). Furthermore, as dictated by Newtonian Physics, torque is equal to the applied force times the lever arm, which is the distance from the applied force to the pivot point (recall Figure 3-12). Therefore, the more distally placed chopper will induce a greater torque (see larger blue vector arrow in nucleus) that will be more likely to break the vacuum seal at the phaco tip and preclude an efficient chop. The correct vertical chopper placement, therefore, is about 1 mm distal to the phaco tip, a position that minimizes induced torque but provides a slight buffer against the initial chopper placement itself inducing a premature fracture plane that breaks the vacuum seal, a situation that could occur if the chopper were directly juxtaposed to the phaco tip. A slightly more advanced technique involves initially placing the chopper on the anterior nucleus at a point midway between where the two choppers were illustrated in Figure 3-27-1 and dragging it toward the phaco tip as it is pushed posteriorly so that it ends up as shown in Figure 3-27-2, just where the proximal chopper would have been from Figure 3-27-1. This technique, which is derived from Steve Arshinoff's Slice and Separate Method, also minimizes induced torque by this vectored approach to the desired endpoint.

Even with ideal chopper placement, note the fundamentally different vector forces involved with vertical chopping as opposed to horizontal chopping in that the latter causes mechanical entrapment of the nucleus as the chopper and phaco tip are drawn horizontally together. This mechanical entrapment allows for a reduced vacuum level during the actual chop (recall Figure 2-16-3). Vertical chopping, however, utilizes forces at right angles to the phaco needle that never mechanically trap the nucleus and therefore requires a sustained high vacuum level to maintain a stabilizing grip of the nucleus until the chop is completed (recall Figure 2-17).

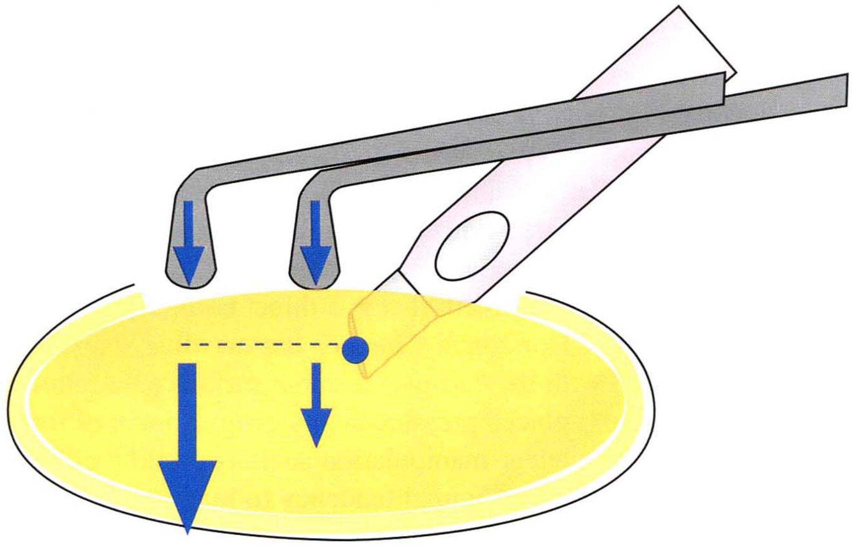


Figure 3-27-1

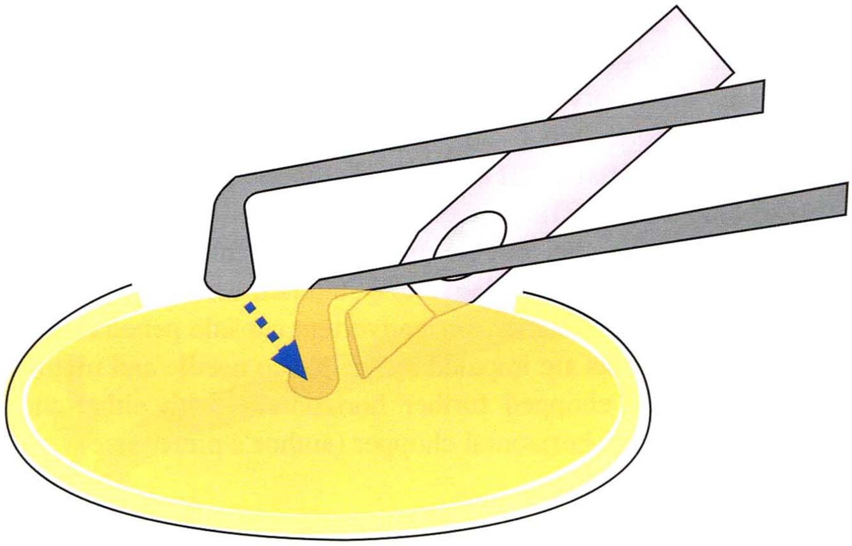


Figure 3-27-2

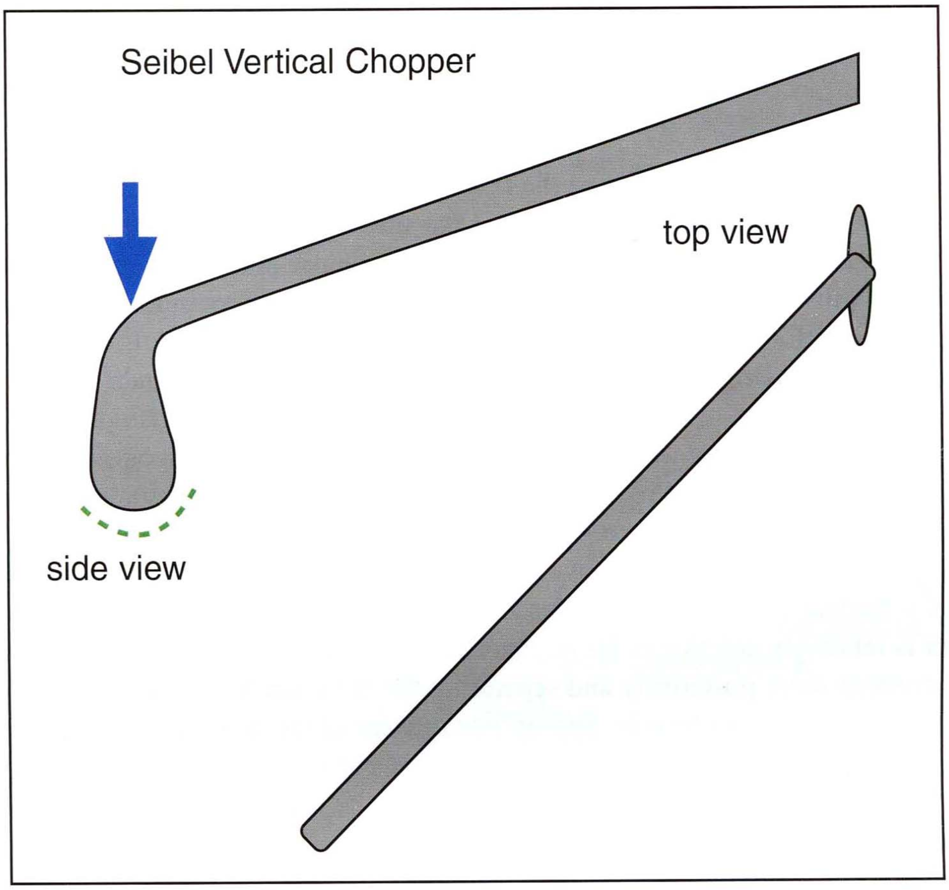
FIGURE 3-27

Chopper Instrumentation

Many chopping surgeons use both horizontal and vertical methods, often within a single case, and this practice underscores the importance of correct instrument selection for each method in order to maximize efficiency and safety. Figure 3-28 illustrates both types of choppers as present on either end of the double-ended instrument manufactured for me by Rhein Medical (#05-4065-R). In the side view, both tips are somewhat similar in that they are rounded distally. However, the top view (as if looking down on the instrument from the direction of the blue arrow) illustrates the profound difference between them that is a direct corollary of their function in the two different procedures. The Seibel Horizontal Chopper has an olive-shaped tip that provides maximum safety in case of contact with the capsule; its large surface area minimizes the chance of inadvertent penetration because of reduced pressure at any given amount of force. This expanded surface area is also beneficial in nuclear manipulation such as rotation and cracking because the tip effectively pushes the nucleus with minimal tendency to inadvertently penetrate into it as might the smaller tip of a standard chopper. The chopping edge on the inner curvature (green dashed line) effectively cleaves the nucleus when drawn in a horizontal fashion.

The tip of the Seibel Horizontal Chopper, however, would be a very poor choice for vertical chopping for the very reason that it is so effectively safe for horizontal chopping; its large surface area and subsequent high resistance to tissue penetration means that it would be very difficult to impale into the nucleus from above as is required for vertical chopping. For this purpose, vertical choppers have a relatively sharp posterior edge. However, most vertical choppers achieve this sharpness by a shape resembling an ice pick. While this design is successful for vertical chopping, it nevertheless sacrifices the safety margin in case of inadvertent capsule contact. The Seibel Vertical Safety Chopper addresses this issue by having a beveled edge (green dashed line) on the posterior perimeter of a curved, flat distal surface (see top view as if looking down on instrument in the direction of the blue arrow). The flatness and beveled edge allow the design to work in all but the very densest, brunescent nuclei, but the rounded curve ensures that any capsule contact will be distributed over a larger surface area relative to a standard vertical chopper, thereby enhancing the safety margin and reducing the chance for inadvertent capsule penetration.

When the chopped fragments are impaled by the phaco needle and mobilized centrally with vacuum for grip, they can be chopped further horizontally with either the vertical chopper (because of its thin profile) or the horizontal chopper (author's preference).


Seibel Vertical Chopper
top view
side view

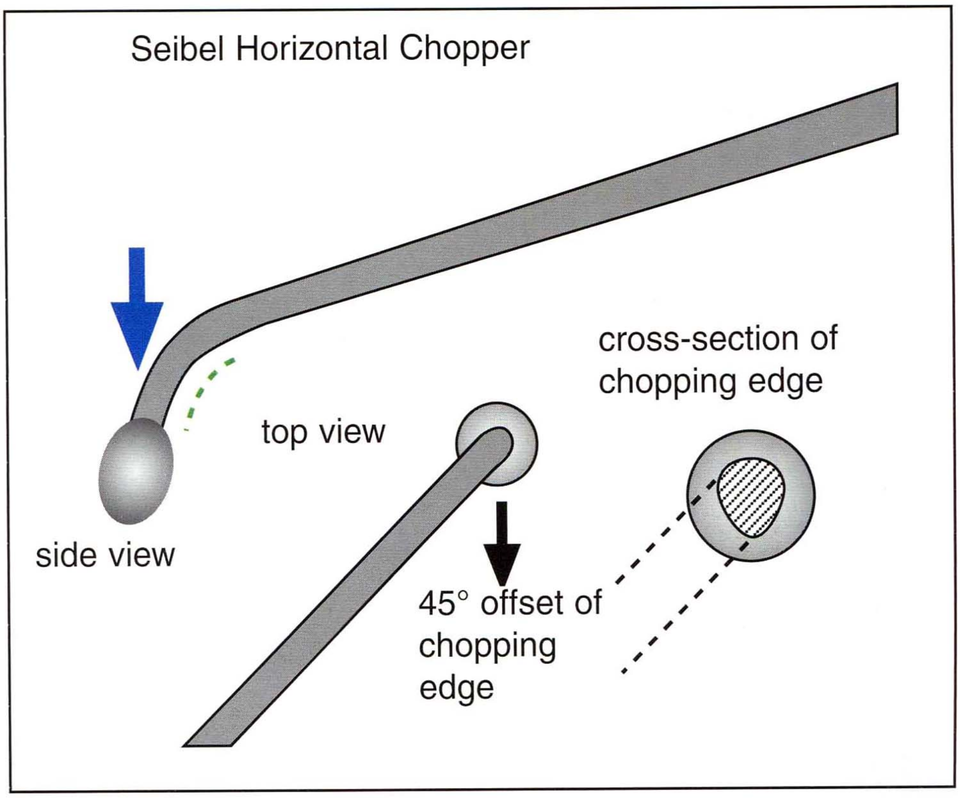

Seibel Horizontal Chopper
cross-section of chopping edge
top view
side view
45° offset of chopping edge

FIGURE 3-28

Akahoshi Prechop

Dr. Takayuki Akahoshi developed the Prechop method to mechanically subdivide the nucleus prior to any delivery of ultrasound energy. Like vertical chopping, it depends on sharp instrumentation that can penetrate the nucleus without pushing it and stressing zonules. In fact, the instrumentation must be even sharper because unlike vertical chopping, the Prechop instrument has no vacuum grip for stabilizing force and must rely entirely on the delicate zonular apparatus for nuclear support (1+ to 2+ nuclear sclerosis). Dr. Akahoshi recommends the use of a chopper to brace and stabilize the nucleus against the Prechopper instrument (Figure 3-29-2) in cases involving denser nuclei (more than 2+), compromised zonules, or an incomplete capsulorrhexis.

Figure 3-29-1 shows the Prechop instrument introduced into the nucleus as seen in a **side view**, with Figure 3-29-2 showing the same placement from the **top view**, along with the optional chopper placement as described above. By separating the jaws of the instrument by squeezing the handle, a nuclear crack is produced as shown in Figure 3-29-3. The initial placement of the Prechopper is relatively anterior in the nucleus, and the crack may need to be completed by moving the instrument more posteriorly and separating the jaws again (see Figure 3-18-1). Quadrants can be created in a similar fashion by appropriate rotation of the newly created heminuclei, always respecting the distance between the peripheral capsule and the sharp Prechopper's tip. Once a sufficient number of fragments has been created, they may be removed like quadrants or further horizontally chopped prior to phacoaspiration.

Dr. Akahoshi has designed different Prechoppers for various nuclear densities, with sharpness increasing for increased densities of nuclei. Just as sufficient ultrasound power is required for sculpting without stressing zonules, the Prechopping surgeon must choose a Prechopper with appropriate sharpness for a given nuclear density to achieve the same goal. However, using Phacodynamic principles of safety (ie, using the least force or parameter possible to achieve a given clinical goal), a sharper Prechopper should not be used when a less sharp instrument would function well.

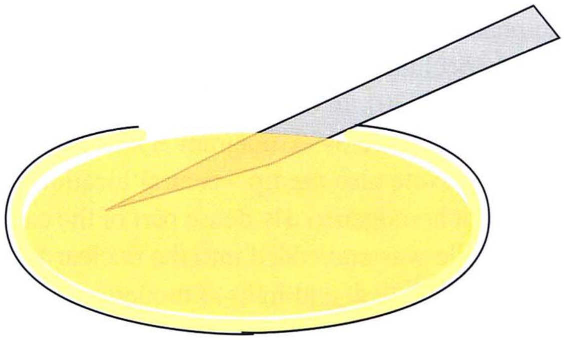


Figure 3-29-1

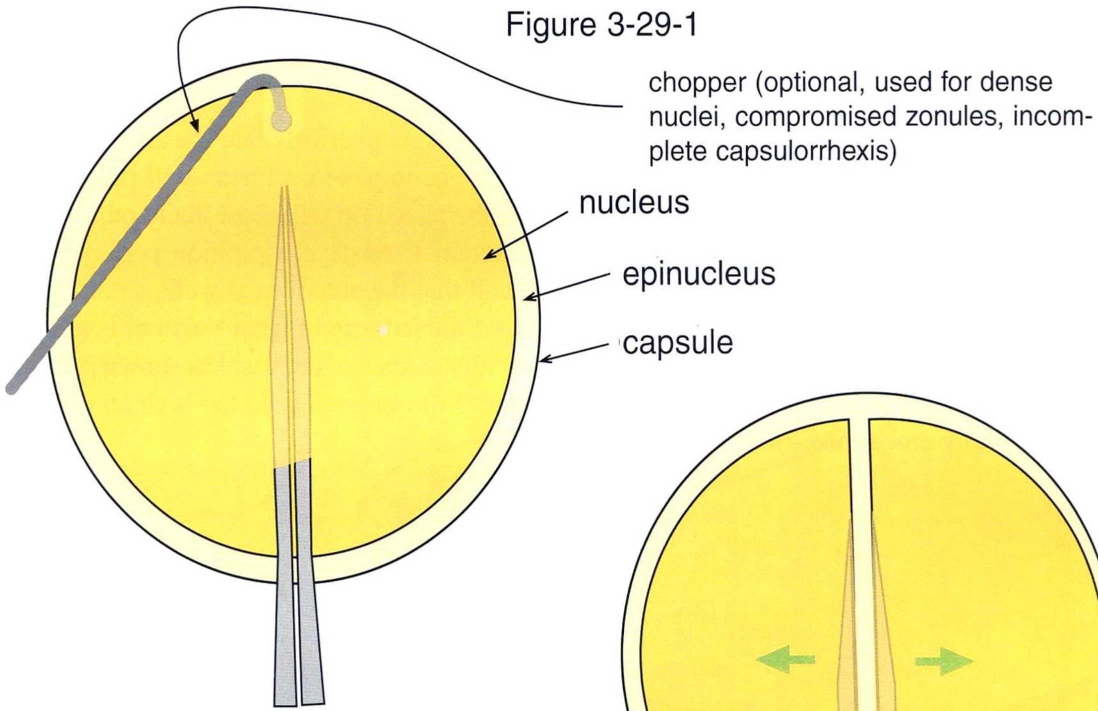


Figure 3-29-2

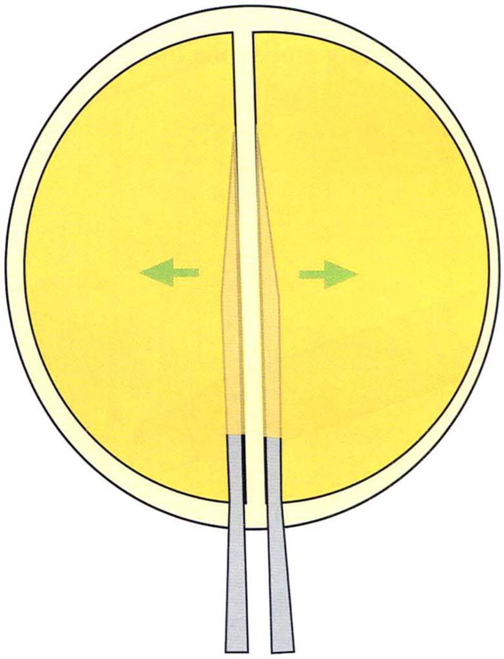


Figure 3-29-3

FIGURE 3-29

Vacuum Seal

Whenever the phaco needle is used to pull the cataract (or segment thereof), the aspiration port must be completely occluded in order to effectively transfer the pump's vacuum as a gripping force (see Figures 1-11 and 1-30). In order to optimally occlude the aspiration port, a good vacuum seal must be achieved (Figure 3-30, diagram A). Note that the tip is embedded 1 to 1.5 mm into the nuclear fragment. Note also the tip's central location in the fragment's anterior-posterior dimension; this is the most homogeneously dense part of the cataract and will provide the best vacuum seal. The phaco needle was embedded into the nuclear face with the needle bevel parallel to the nuclear face that was occluded, and light to moderate linear pulse mode ultrasound was used to ensure a tight vacuum seal surrounding the tip. Once the needle was embedded as shown, the foot pedal was raised from position 3 to position 2 in preparation for manipulating the nuclear fragment; recall that a vibrating phaco needle (position 3) would be more likely to disinsert from the fragment rather than gripping and pulling it.

Diagram B shows the phaco tip engaging the cataract so anteriorly that the aspiration port is exposed to the anterior chamber fluid (red arrow); this incomplete occlusion will preclude optimum gripping of the nuclear fragment. When pulled, the phaco tip will most likely pull out of the fragment rather than pull the fragment with it. Diagram C has the aspiration port completely occluded, but it is still too anteriorly positioned. Recall that the anterior (as well as posterior and peripheral) nucleus is often not as dense as the central nucleus, and higher vacuum levels might preferentially aspirate the less dense material, compromising the vacuum seal as shown in diagram D (red arrow). This situation could also have occurred if the surgeon used too high an ultrasound level to initially embed the tip.

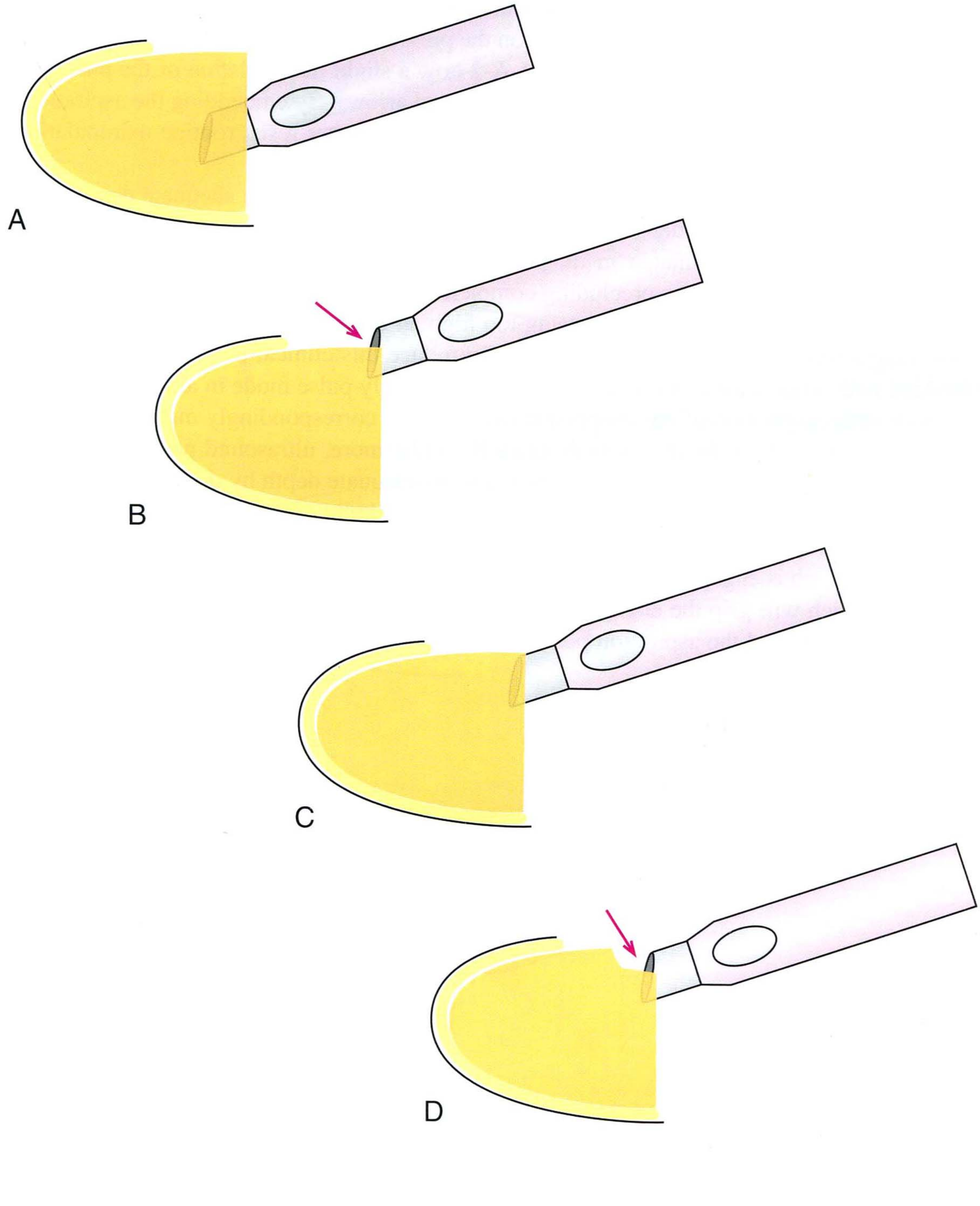


Figure 3-30

Vacuum Seal (continued)

In diagram A-1 of Figure 3-31, the aspiration port is completely occluded in the correct central face of the nuclear fragment as described on the previous page. However, the tip is not embedded to a sufficient depth. Note in Figure 3-31-A-2 how a slight manipulation of the phaco needle (blue arrow) has caused a break in the vacuum seal (red arrow). By embedding the aspiration port to an adequate depth of 1 to 1.5 mm, the vacuum seal can better resist routine manipulations of the tip without breaking and causing loss of gripping control.

Diagram B of Figure 3-31 illustrates the phaco tip embedded to an adequate depth and positioned properly in the central densest nucleus, with a good potential for a vacuum seal. However, that potential has been eliminated in diagram C because too much nuclear material has been removed around the tip, thereby precluding complete occlusion of the aspiration port. Two conditions could lead to this problem. First, using too high an ultrasound power and/or maintaining it for too long a time when embedding the tip will produce this clinical picture. The tip should be embedded with mild linear controlled ultrasound (preferably pulse mode in anticipation of occlusion-mode phacoaspiration of the chopped fragment) with correspondingly minimal cavitation in order to achieve the tight fit shown in diagram B; furthermore, ultrasound power should be discontinued immediately once the tip is embedded to an adequate depth by disengaging pedal position 3 while maintaining pedal position 2 to maintain and build vacuum and gripping force. The second condition that could lead to diagram B is the use of too high a vacuum level for the density of nucleus which is engaged. Vacuum should ideally be titrated with linear control to an appropriate level which will grip the engaged fragment without being so high that it abruptly aspirates the material just around the aspiration port (recall Figures 1-12 and 1-31).

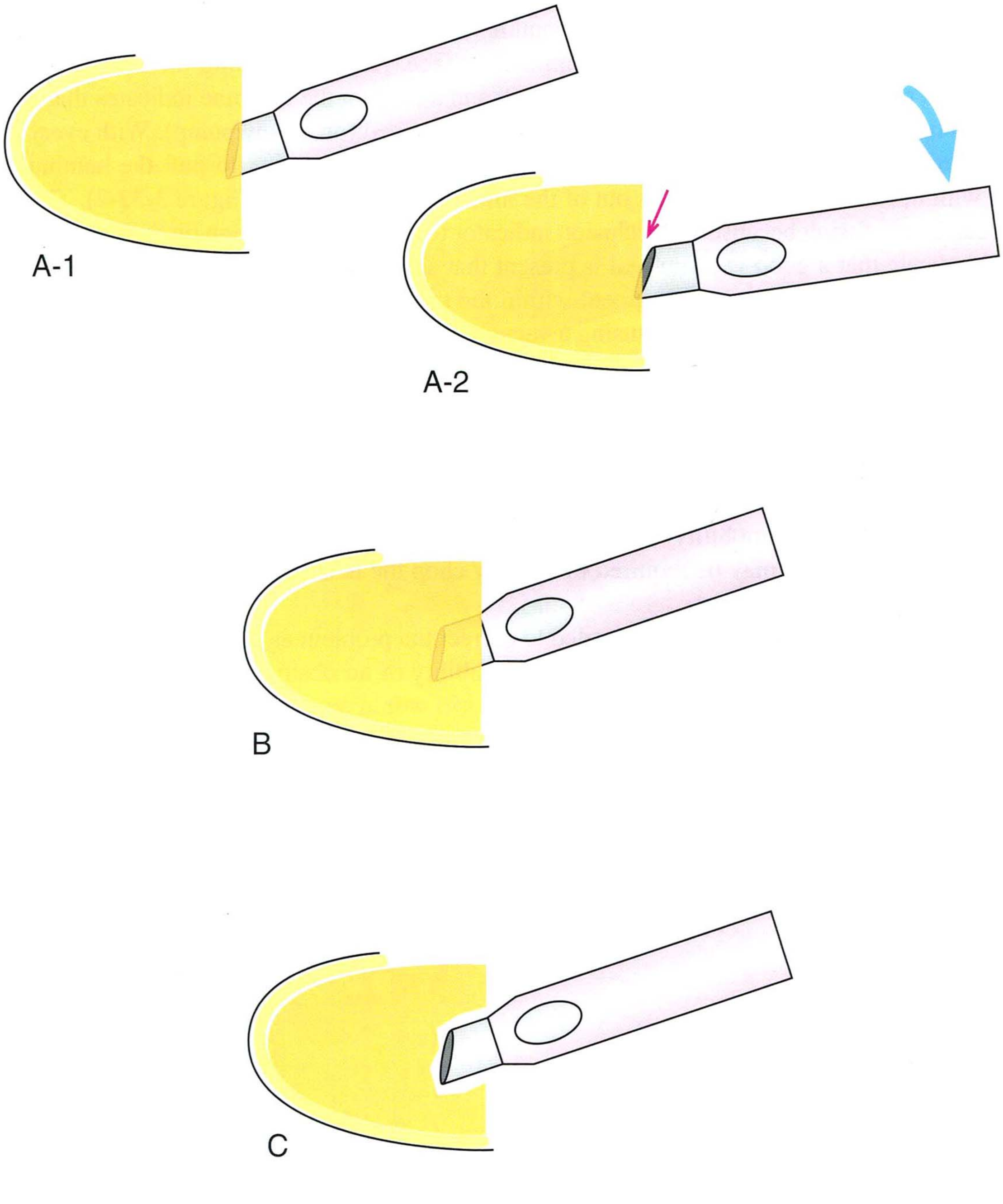


FIGURE 3-31

Vacuum Seal (continued)

Figure 3-32-1 appears to be a good vacuum seal with the tip buried tightly to an adequate depth in the central densest part of the heminuclear face. After embedding the tip, the pedal is raised from position 3 to the bottom of position 2, and a tone on the machine indicates that occlusion is obtained and the vacuum preset limit has been attained (on a flow pump). With everything thus optimally set up, the surgeon retracts the phaco needle, expecting to pull the heminucleus along with it, but instead the tip pulls out of the immobile heminucleus (Figure 3-32-2). This scenario can be confusing because the occlusion indicator tone along with a high pitched vacuum tone would indicate that a good vacuum seal is present that should be providing a good grip.

The problem is the nuclear fragment within the tip that has broken away from the heminucleus and is clogging the distal tip, causing a vacuum buildup between it and the pump, leading to the occlusion indicator tone. By briefly stepping into position 3, the clog usually can be readily cleared by ultrasound, resulting in a cessation of the occlusion tone and typically a drop in pitch of the vacuum tone, indicating lowered vacuum with restored flow. This scenario indicates to the surgeon that this particular nuclear density may not have sufficient structural integrity to sustain adequate levels of vacuum for gripping, at least in the first phases of chopping when the surrounding nucleus limits mobility of the engaged fragment. Therefore, a traditional Nagahara (Figure 2-14) dissection may be required to initially chop the heminucleus in situ to produce and remove the first few fragments.

If brief applications of ultrasound failed to correct the problem as discussed in the preceding paragraph, then the surgeon must consider the possibility of an obstruction in the aspiration line between the phaco needle and the pump. This scenario would also result in an occlusion indication and a high vacuum tone along with poor grip and a visibly unoccluded aspiration port. In this case, the surgeon would discontinue the operation and troubleshoot the fluidic circuit to dislodge the obstruction (eg, flush out ultrasonic handpiece, inspect aspiration line for clogs, kinks, etc).

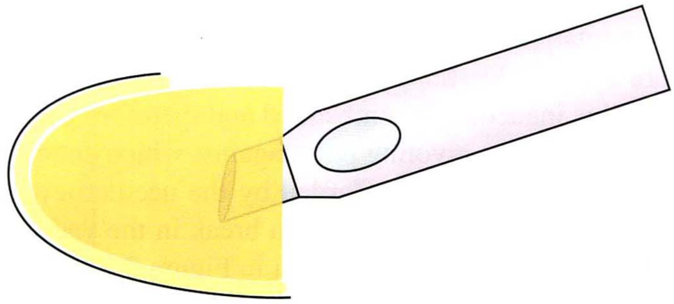


Figure 3-32-1

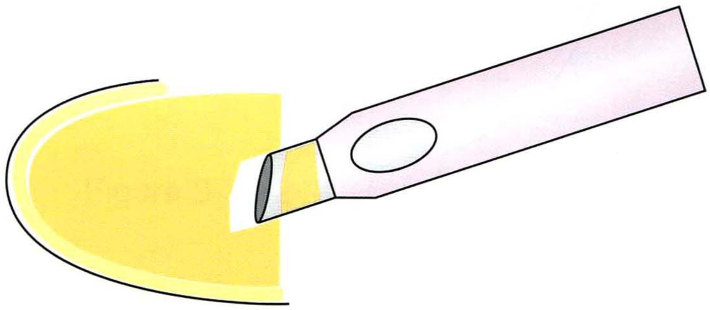


Figure 3-32-2

FIGURE 3-32

Vacuum Seal: Needle Bevel

The weakest point of a vacuum seal is the shortest distance that the aspiration port is embedded into the nucleus. Orienting the phaco needle so that the bevel is parallel to the surface to be impaled insures that this distance is uniform across the entire aspiration port, as shown in Figure 1-59A. This parallel orientation also ensures a stable platform against which force may be directed in a perpendicular fashion (green arrow) by a horizontal chopping instrument, as shown in Figure 3-33-1. Incorrect orientation of the needle bevel relative to the nuclear face promotes instability in two ways (Figure 3-33-2). First, although side "A" of the needle is embedded adequately into the nucleus, side "B" is inadequately embedded and therefore prone to loss of the vacuum seal. Second, point "C" is an unstable pivoting point against which chopping force is directed, as opposed to the stable perpendicular surface afforded by the needle bevel in Figure 3-33-1. The combination of these two factors will often result in a break in the vacuum seal at point B and a loss of grip when chopping force is applied, as shown in Figure 3-33-3.

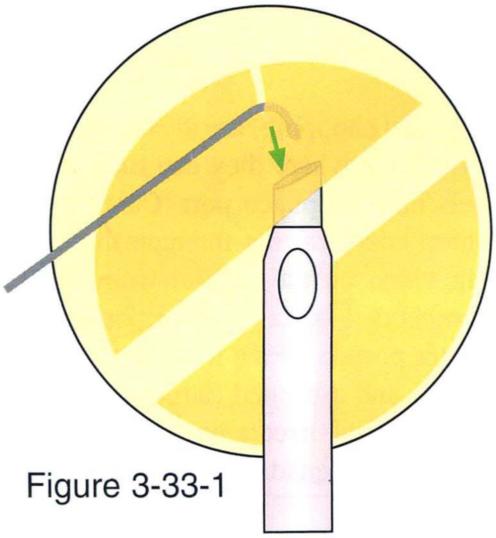


Figure 3-33-1

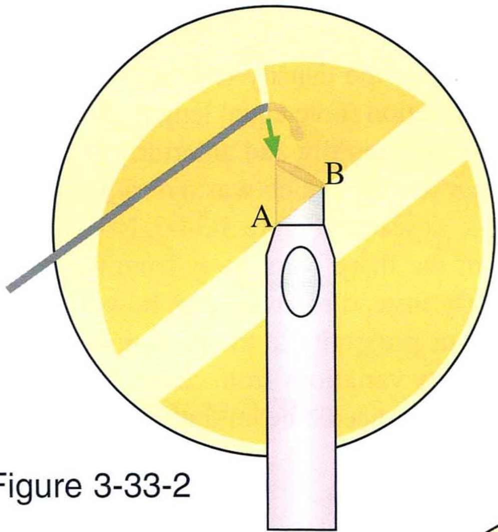


Figure 3-33-2

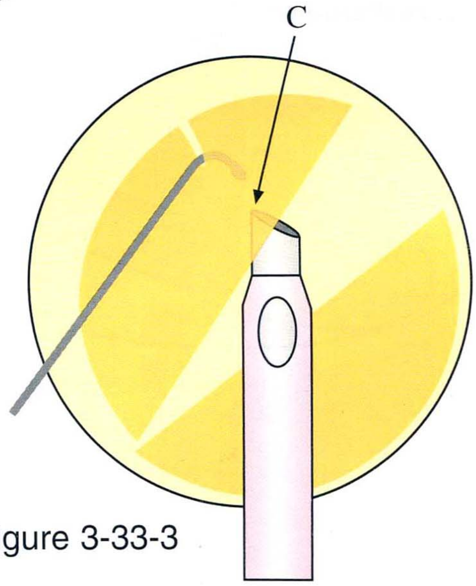


Figure 3-33-3

FIGURE 3-33

Fragment Manipulation 1

Nuclear quadrants (or smaller segments produced by phaco chopping) are ideally pulled with the phaco tip to the center of the posterior chamber or iris plane where they can then be safely emulsified as a free-floating mass which readily carousels into the phaco port. Care should be taken when initially moving the quadrant so that any sharp edges do not threaten the capsule, notwithstanding Dr. Robert Osher's grand prize-winning video on the subject from the 1997 ASCRS Film Festival. Figure 3-34-1 has the phaco tip embedded in the anterior portion of the quadrant with ultrasound engaged. Note how the softer outer portion of the nuclear fragment by the upper part of the needle bevel is more rapidly emulsified and aspirated (larger green arrow) relative to the harder inner portion engaged by the lower part of the needle bevel (smaller green arrow). This differential causes a quadrant rotation with the sharp quadrant point being rotated directly against the capsule (red circle).

Figure 3-34-2 depicts a safer method of engaging the quadrant by applying ultrasound power in the center of the quadrant where the density is homogeneous; the quadrant is drawn directly onto the phaco needle without rotation (note equal length green arrows). With it safely engaged in this fashion, it can then be moved centrally and anteriorly for complete phacoemulsification and aspiration. The variable nuclear density which was a disadvantage in Figure 3-34-1 can theoretically be used to your advantage as seen in Figure 3-34-3. Note how the same principles are applied in reverse to induce rotation of the sharp point away from the posterior capsule by initially placing the phaco needle posteriorly instead of anteriorly; however, this maneuver places the aspiration port in potentially dangerous proximity to the posterior capsule.

In addition to nuclear density variations from center to peripheral, the above behavior of the nucleus is predicated on a 30° distal needle bevel that is placed vertically parallel to the quadrant face, as illustrated.

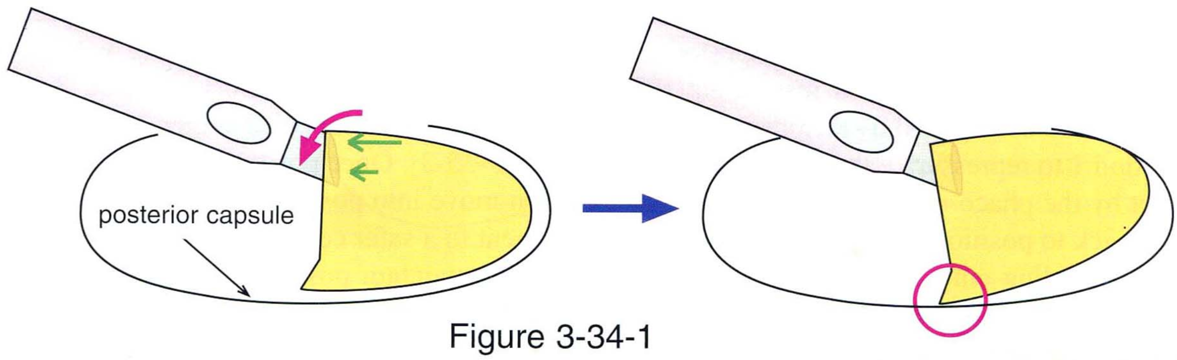


Figure 3-34-1

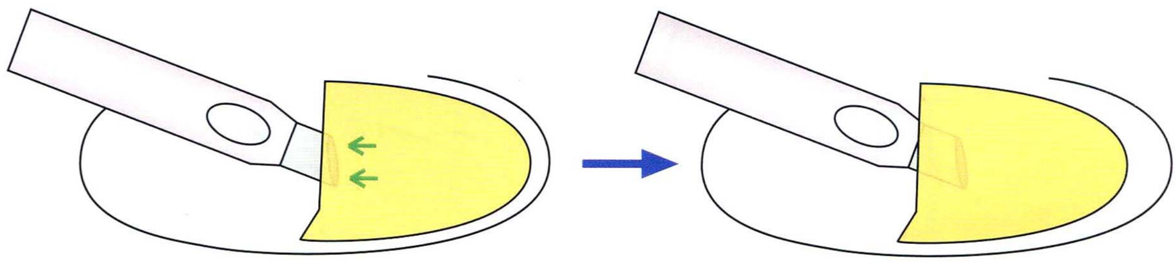


Figure 3-34-2

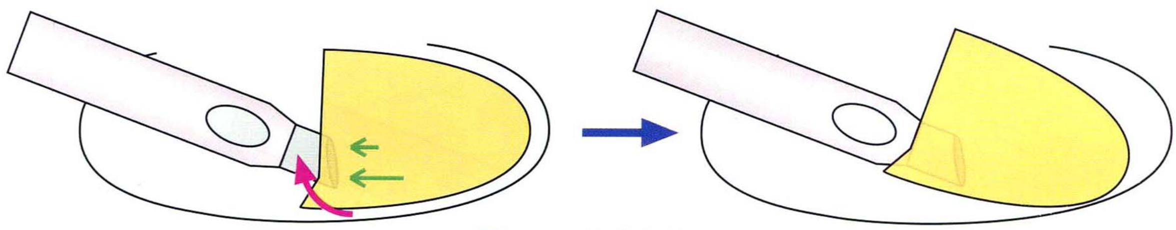


Figure 3-34-3

FIGURE 3-34

Fragment Manipulation 2

Another method of handling the sharp point of the quadrant is by engaging it within the lumen of the phaco needle. This maneuver can be accomplished by first moving to pedal position 0 on the foot pedal, thereby decreasing the IOP (see Figures 1-7 and 1-24). The vitreous pressure will then make the center of the posterior capsule protrude anteriorly; this along with gentle manipulation by the second instrument tips moves the sharp point anteriorly (Figure 3-35-1), where it can be engaged by the phaco needle (Figure 3-35-2). The foot pedal is then depressed into position 1 to repressurize the anterior chamber (Figure 3-35-3). Once positive control of the sharp point by the phaco needle is established, you can then move into position 3 to embed the tip and then back to position 2 to grip and mobilize the fragment to a safer central location in preparation for carouseling emulsification. Alternatively, one could maintain position 3; because the phaco needle is engaging the posterior nucleus, activating ultrasound power will continue to rotate the point safely up as in Figure 3-35-3. As with Figure 3-34-3, caution must be exercised because of the proximity of the phaco tip to the posterior capsule.

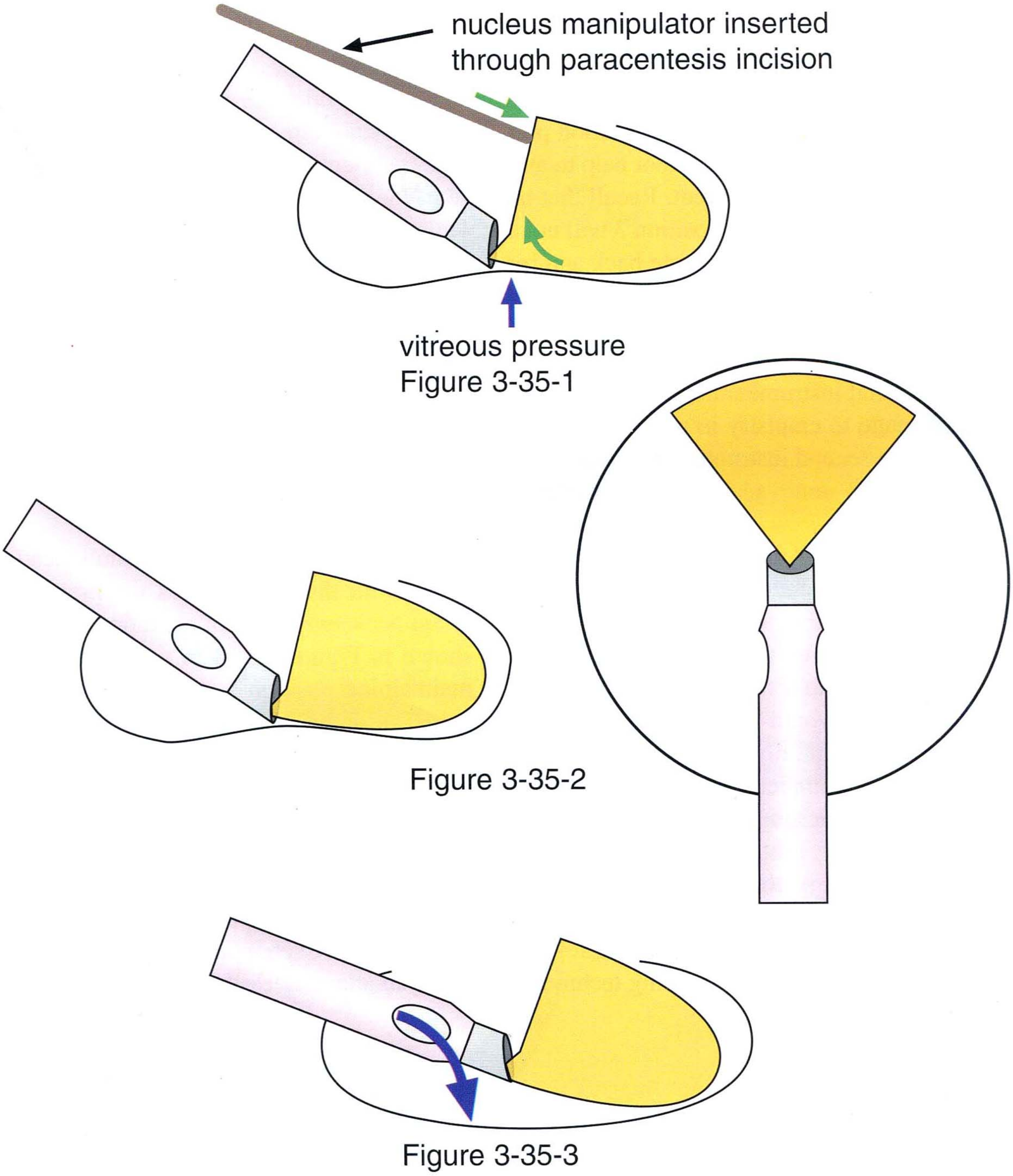

nucleus manipulator inserted
through paracentesis incision
vitreous pressure
Figure 3-35-1
Figure 3-35-2
Figure 3-35-3

FIGURE 3-35

Fragment Manipulation 3

The phaco tip in Figure 3-36A has impaled a nuclear fragment, boring almost completely through it. Maintaining pedal position 3 in this case invites disaster because of the aspiration flow (red arrow) tending to draw unwanted material like iris or capsule into the port. Furthermore, without complete occlusion of the aspiration port, vacuum cannot effectively aid in aspirating the fragment; similarly, the flow does not help to aspirate the fragment because fluid is drawn into the tip prior to affecting the fragment. Recall that because of the axial orientation of ultrasound needle vibration, continuation of position 3 will not accomplish any further emulsification of the fragment; the needle will simply vibrate back and forth along the axis of the hole it has bored. Lastly, the phaco needle cannot progress any further through the fragment because of the physical obstruction from the silicone irrigation sleeve (see Figures 3-2 and 3-3).

The correct move in this case is to back off to position 1 to maintain the anterior chamber; then use a second instrument through the side-port incision to push the fragment off of the phaco tip and reengage to emulsify in a carouseling fashion, manipulating and feeding the fragment to the tip with the second instrument as necessary (Figure 3-36C). Note how the segment's sharp tip was ultrasonically removed prior to carouseling in order to prevent it from spinning into the capsule or cornea.

Engaging fragments in a tangential fashion for carouseling enables efficient emulsification as both flow and vacuum continue to feed new material into the phaco tip as the previously engaged portion is emulsified and aspirated in an efficient occlusion mode of operation.

Note the nontangential fragment engagement shown in Figure 3-36B in which the phaco needle has bored into a thick part of the fragment; maintaining position 3 with a dense nuclear sclerotic fragment would not produce any further emulsification because the silicone sleeve will prevent vacuum from drawing the fragment any further into the needle. Furthermore, because the aspiration port is completely occluded, maintaining position 3 will cause potentially dangerous heat buildup from incisional friction caused by the vibrating ultrasonic needle in the absence of a cooling flow current. Fragments engaged in this fashion should be removed by refluxing or with a second instrument so that they can be reengaged for emulsification in a carousel fashion as in Figure 3-36C. Larger fragments generally require more manipulation by a second instrument to maintain optimum tangential positioning for carouseling; therefore, chopping methods are typically more efficient than quandranting techniques because smaller nuclear fragments are generated.

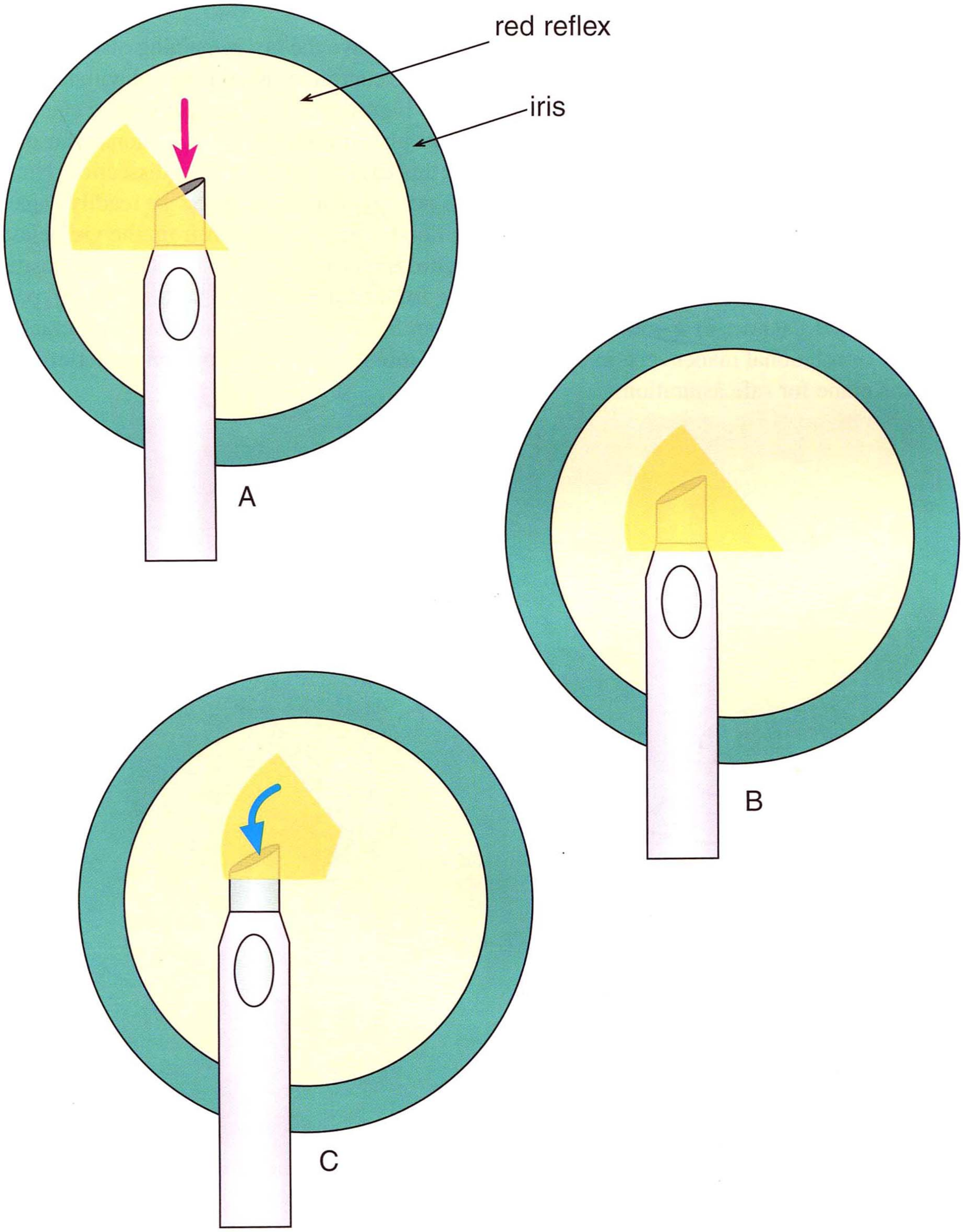


FIGURE 3-36

Fragment Manipulation 4: Viscodissection

Sometimes you will paint yourself into a corner and have the last remaining quadrant at the subincisional position. If you are unable to rotate it to the contraincisional position with an instrument from the side-port incision, use the technique in Figure 3-37-1. The viscoelastic cannula is introduced through the side-port incision with the tip placed under the subincisional rim of the capsulorrhexis as if to perform a hydrodissection; in this case, it will be a viscodissection. Note in Figure 3-37-2 how the fragment has been moved to a position where it can now be readily engaged with the phaco tip; moreover, it is stable in this position because of support from the viscoelastic. This technique is equally successful in dealing with epinucleus at the subincisional position. Additionally, viscodissection is a valuable technique for dealing with very soft nuclei (eg, posterior subcapsular cataract in a young adult), which can be difficult to manipulate with cracking, chopping, or rotational maneuvers, in order to achieve mobilization to the central posterior chamber or iris plane for safe aspiration.

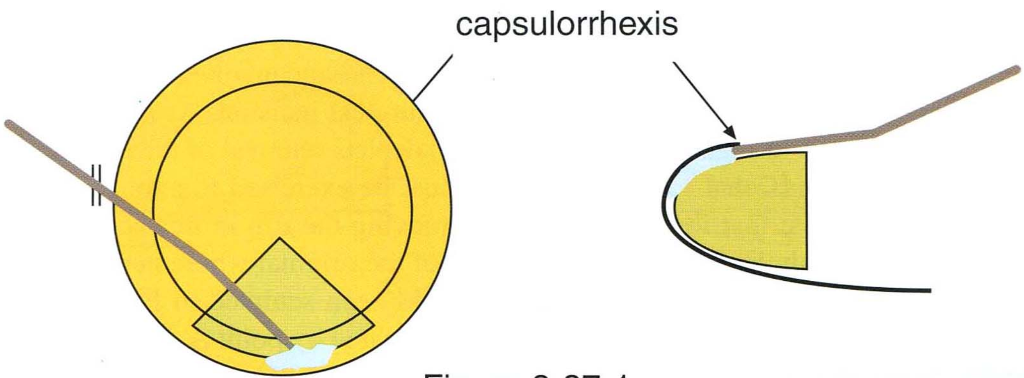


Figure 3-37-1

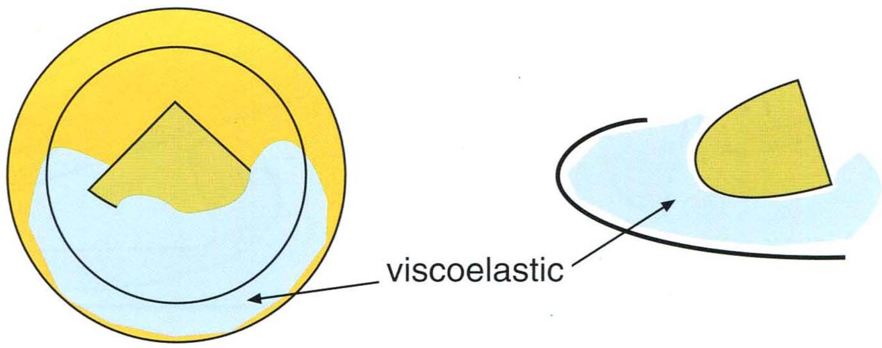


Figure 3-37-2

FIGURE 3-37

One-Handed Strategies 1

A fundamental goal of one-handed techniques, as well as the Kratz/Maloney two-handed technique, is to remove the bulk of the nuclear top, center, and rim so that the remaining posterior nuclear plate is small enough to be freely attracted to the phaco tip for safe carouseling/emulsification in the center of the posterior chamber or iris plane. Both techniques begin with deep central sculpting to debulk the nucleus. Dr. Maloney's original technique involved removal of the rim from peripheral to central at the area closest to the main surgical incision. As an alternative, the one-handed technique shown in Figure 3-38-1 (**side view**) depicts removal of the rim from central to peripheral at the contraincisional location; caution must be exercised to avoid aspirating the contraincisional capsule. Note that in this figure that removing the rim in this sculpting fashion will leave a nuclear plate with the same diameter as that of the original whole nucleus.

Note the different way in which the nuclear bowl has been sculpted in Figure 3-38-2; the contour is such that a thin weak area has been created as indicated by point A. The location of this fault-line predetermines the diameter of the subsequent nuclear plate. Gentle ultrasound is used to embed the phaco tip; the foot pedal is then backed off to position 2 so that when the tip is withdrawn, it uses vacuum to carry the rim with it after breaking it free from the nuclear plate at the weakest area (point A). This technique effectively accomplishes the goal of a resultant nuclear plate with a substantially smaller diameter than that of the original nucleus. Furthermore, the contraincisional capsule is not endangered by the sculpting of the juxtacapsular nuclear bowl as with Figure 3-38-1.

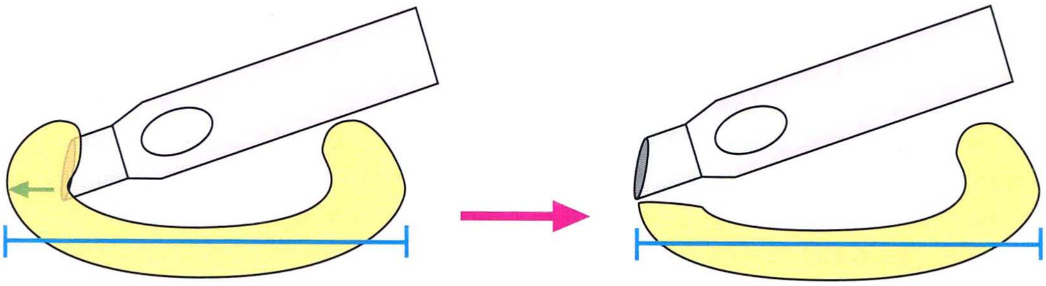


Figure 3-38-1

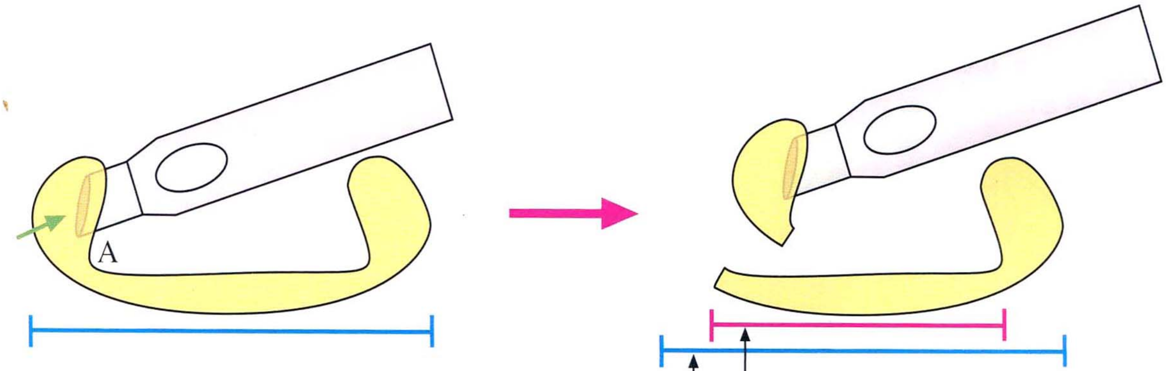


Figure 3-38-2

FIGURE 3-38

One-Handed Strategies 2

An important key to efficiency in phaco surgery is to be always thinking several steps ahead of your current step; by planning each step so that it will facilitate subsequent steps, you will avoid painting yourself into a corner. As an example, let's continue with the procedure begun on the previous page. Figure 3-39-1 shows the microscope's anterior view of the nuclear bowl which has been sculpted out so that a fault-line has been created around the perimeter of the planned nuclear base. The phaco tip is embedded in the nuclear rim as shown using mild ultrasound power and then reverting to pedal position 2 only; the rim segment is then broken free while pulling and maintaining position 2 in Figure 3-39-2. You will sometimes have to facilitate removal of this first section by making phaco nicks in the rim on either side of it. Once this piece has been safely emulsified in the center, the tip is positioned so as to reengage the rim as illustrated in Figure 3-39-3.

At this point, the tip could be pulled to break off another section of rim, but doing so would simply remove the contraincisional portion of the rim while leaving poor access to the remainder of the nucleus; remember by definition that a one-handed strategy does not give you access to a second instrument which could rotate the nucleus to provide more rim in the 6 o'clock contraincisional position. The most effective way to rotate the nucleus with the phaco tip is by pulling (see Figure 3-15), but that will not be possible with the entire inferior section of rim removed. It is possible to rotate it by nudging the nuclear plate, but this has both a poor mechanical advantage as well as a poor safety margin. A better option that sets up subsequent steps is shown by the green arrows in Figure 3-39-3, in which the tip is used to rotate the nucleus using vacuum and grip so that the engaged portion may then be removed at the same clock position as the original segment. By repeating this process, each step sets up the subsequent step until the rim is completely removed and a nuclear plate remains.

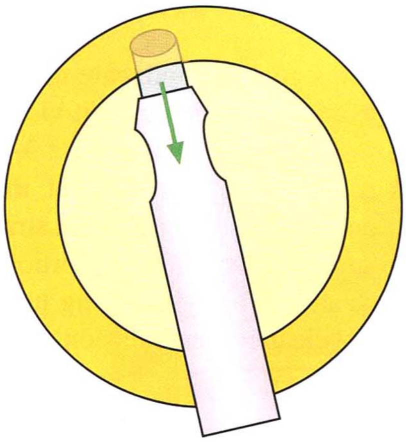


Figure 3-39-1

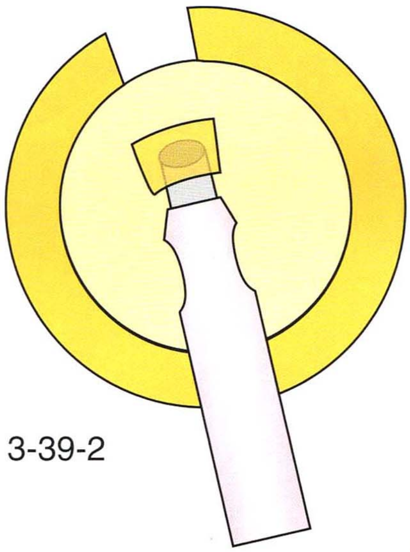


Figure 3-39-2

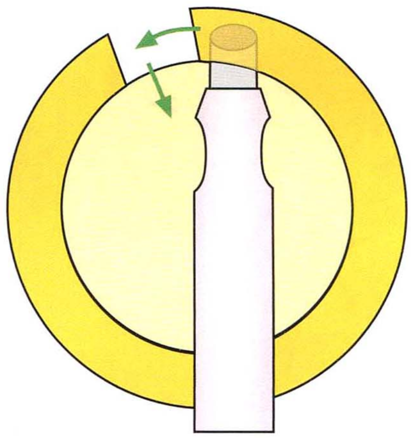


Figure 3-39-3

FIGURE 3-39

Pivot Around Incisions 1

All intraocular maneuvers need optimum visualization. With this goal in mind, care must be taken to pivot around side-port and tunnel incisions to avoid corneal striae, which inhibit visualization, and to avoid wound distortion which can cause leaks and chamber collapse (Figure 3-40-1). In Figure 3-40-2, we wish to move the phaco tip from point A to point B. The shortest, intuitive movement is shown in Figure 3-40-3 (straight red arrow); note the resultant corneal striae. By pivoting around the incision as in Figure 3-40-4 (curved red arrow), this wound distortion is avoided. Sometimes corneal striae are unavoidable, especially when dealing with a long tunnel and anterior corneal entry found in sutureless-style sclerocorneal and clear corneal incisions; however, careful attention to pivoting can still lessen the effect.

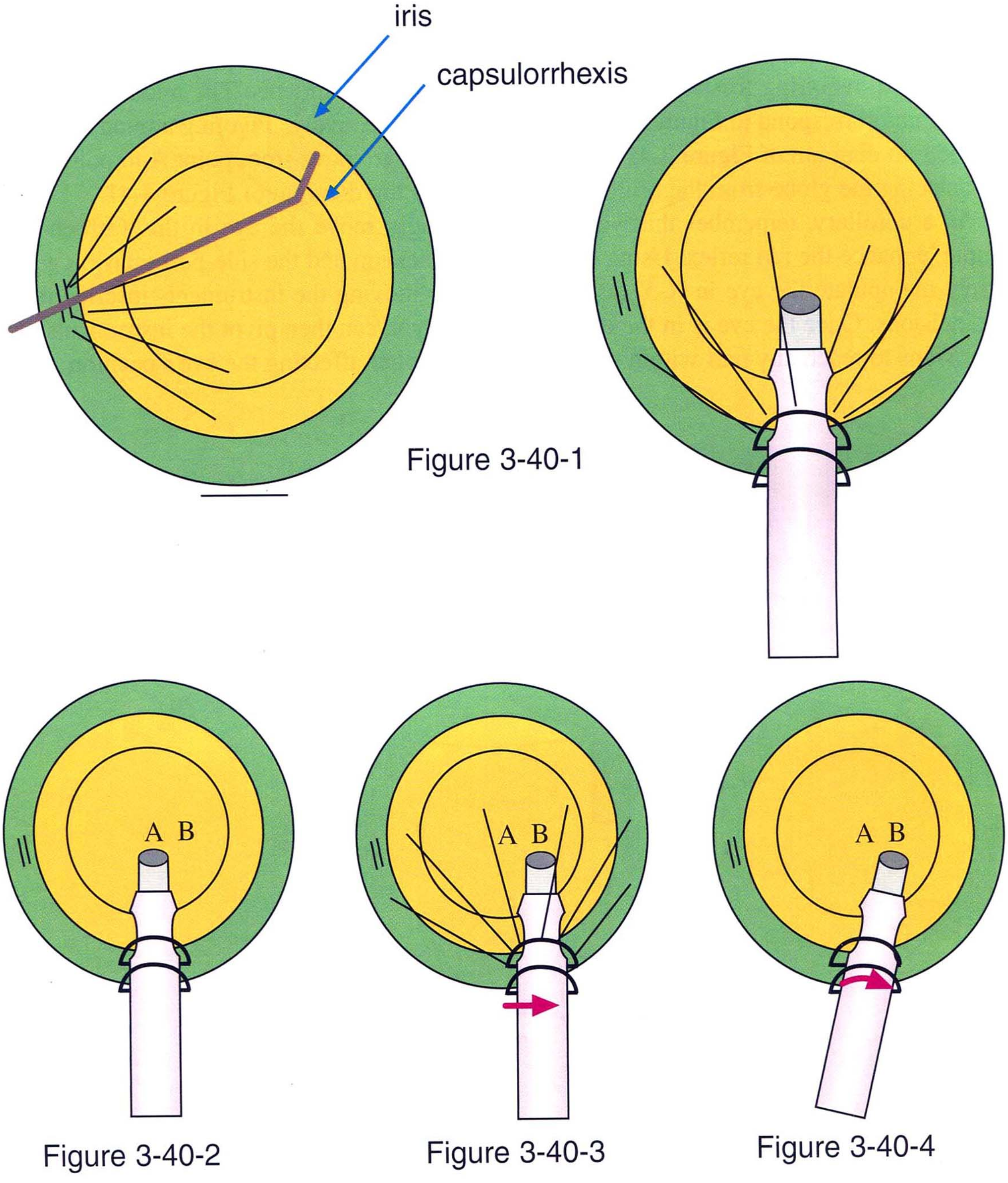

iris
capsulorrhexis
Figure 3-40-1
A B
Figure 3-40-2
A B
Figure 3-40-3
A B
Figure 3-40-4

FIGURE 3-40

Pivot Around Incisions 2

Figure 3-41 illustrates another disadvantage of not pivoting around incisions; the eye is easily decentered, requiring frustratingly frequent X-Y scope adjustments. The middle and the bottom diagrams correspond to Figures 3-40-3 and 3-40-4, respectively. Pivoting around the incision in the bottom diagram of Figure 3-41 allows the phaco tip to move from point A to point B without displacing the globe from the original position in the top diagram of Figure 3-41.

As a corollary, remember that you can intentionally move the eye in this fashion to, for example, enhance the red reflex. Using both the main incision and the side-port incision, you can coarsely manipulate the eye in X-Y fashion by simply moving the instruments inserted through these incisions. Once the eye is in the desired position, you can then pivot the instruments within the incisions to reach any part within the eye without further affecting the eye's position.

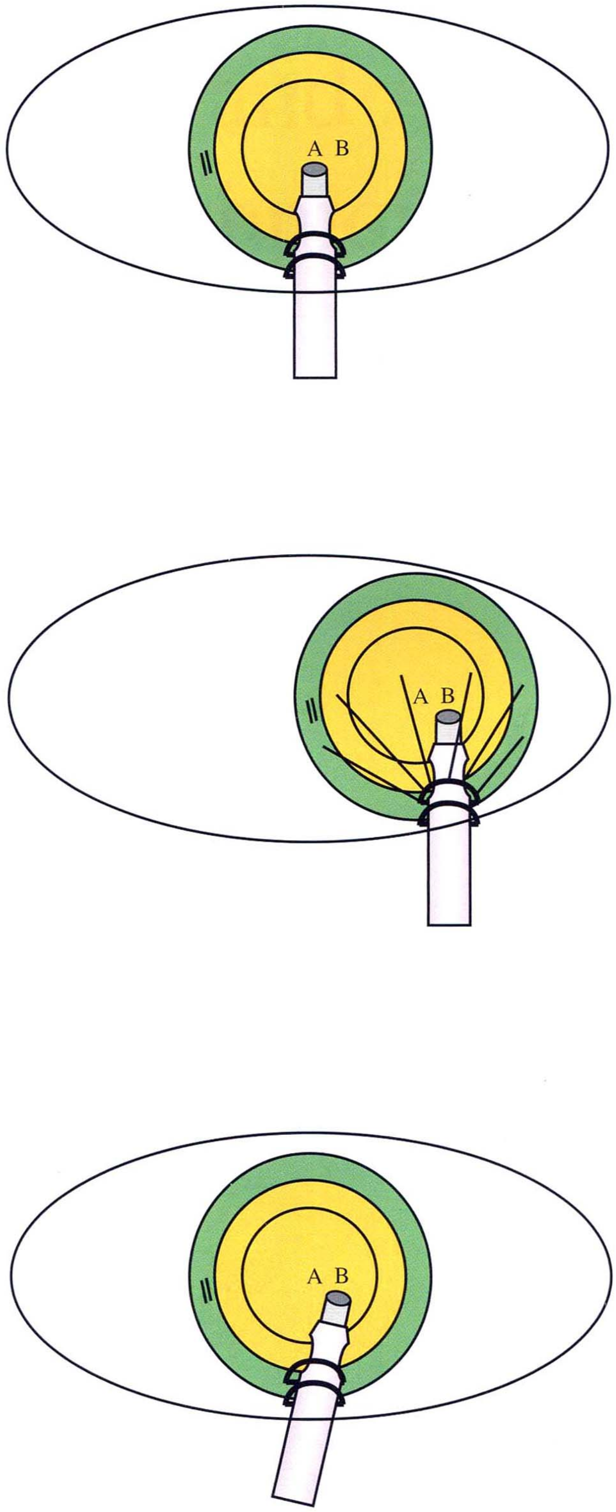


FIGURE 3-41

SECTION FOUR

Irrigation and Aspiration Techniques

Cortical Classification

When phacoemulsification is complete, we would all like to be left with cortex such as that engaged by tip A in Figure 4-1. This soft, thick material is readily engaged and aspirated. However, this is not the case with the thin, diaphanous strands of cortex drawn into tip B. Because these strands lack sufficient volume to completely occlude the tip, flow is often of greater importance than vacuum in optimizing machine parameters; the frictional force of a rapid flow over the cortical strands functions to pull them along with the flow current. When using a vacuum pump, flow and vacuum **autoregulate** (see Figure 2-5) their effect on the strands relative to the proportion of the tip that is unoccluded vs occluded, respectively; if the strands are not being effectively aspirated, the surgeon simply increases the commanded vacuum level.

The effect of flow and vacuum is perhaps better illustrated when using a flow pump. If a low flow rate is used (ie, 10 cc/min), the strands at tip B might be drawn into the aspiration port, but it is unlikely that they will be effectively aspirated from the eye, even if a high vacuum preset level is set. The reasoning is two-fold. First, low flow rates will not effectively build vacuum with a mostly unoccluded IA tip even if a high preset vacuum limit is chosen (see Figure 1-41). Furthermore, the slow flow does not exert sufficient frictional force on the strands to draw them away from their capsular adhesions. Therefore, one should use a more effective higher flow rate when dealing with cortical strands (eg, about 35 cc/min to 45 cc/min); **moreover, the vacuum limit must be set high enough so that the pump does not stop when resistance to flow raises the vacuum in the aspiration line**. For example, note in Figure 1-41 that a commanded flow of 30 cc/min produces a vacuum inside the 0.3 mm IA tip of 200 mm Hg. The preset vacuum level should therefore be set higher (eg, 350 mm Hg) so that flow can be maintained through a partially or non-occluded tip. If a vacuum limit of 100 mm Hg were instead used, the flow would never build past 20 cc/min even though the commanded flow was set to 30 cc/min; the reason would be the feedback loop from the vacuum limit stopping the pump when vacuum had built to the preset of 100 mm Hg from fluidic resistance through the unoccluded IA tip at 20 cc/min.

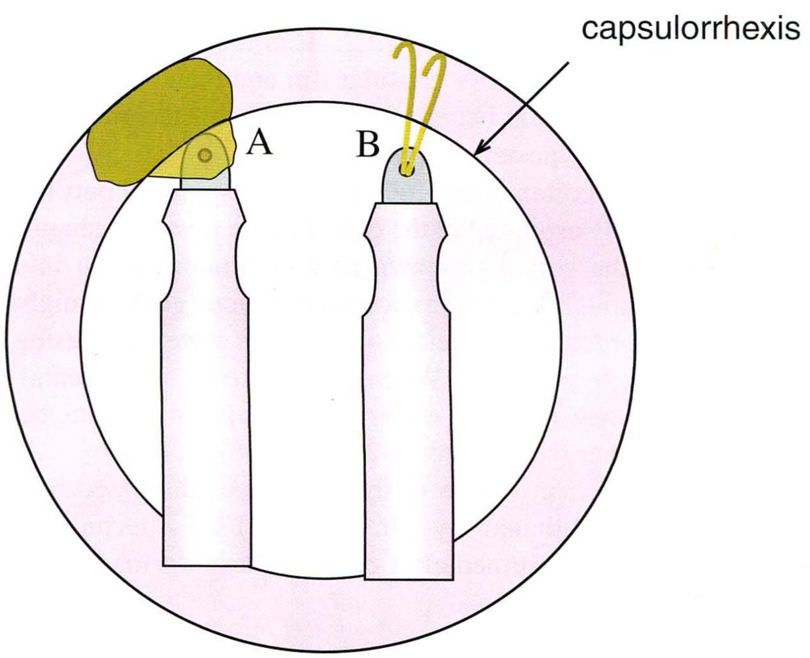


FIGURE 4-1

Cortical Removal: Large Pieces Instead of Small Bites

With the IA tip positioned as in Figure 4-2-1, you have a couple of options. You could fully depress the IA pedal and readily aspirate a small chunk of cortex (assuming a high vacuum preset level); however, this maneuver would have some disadvantages. First, you would have to reengage and reaspirate many times to remove all of the cortex if you are taking only a small amount at a time. Secondly, aspiration of in situ cortex increases the danger of inadvertently aspirating adjacent structures such as iris and capsule. A better technique is to use linear vacuum control and to only depress the foot pedal far enough into position 2 to firmly engage the cortex without aspirating it. As the tip is then moved toward the center of the posterior chamber, the engaged cortex is gently peeled away as shown in Figure 4-2-2. This technique is further facilitated by initially engaging the cortex under the anterior capsular rim and then peeling it centrally; any inadvertent capsule incarceration would be far better tolerated with this technique as opposed to engaging the cortex adjacent to the thinner posterior capsule.

With a large piece of cortex completely free, the aspiration port is then turned superiorly so that the cortex can be safely aspirated in the center of the posterior chamber. The foot pedal is then depressed further until the cortex is drawn as a continuous piece into the tip (Figure 4-2-3). Remember to use just enough vacuum to accomplish your goal. It might be unnecessary to fully depress the IA pedal in order to completely aspirate the cortex, and using more vacuum than necessary decreases your safety margin. When you make an incremental increase in vacuum by depressing the pedal to a new position, remember to wait for rise time before deciding whether to increase vacuum still further (see Figures 1-22 and 1-38).

Notwithstanding the effectiveness of the techniques discussed heretofore, cortical removal can usually be further facilitated by Dr. Howard Fine's technique of **Cortical Cleaving Hydrodissection**, which is performed after capsulorrhexis formation but prior to phacoemulsification (Figure 3-10).

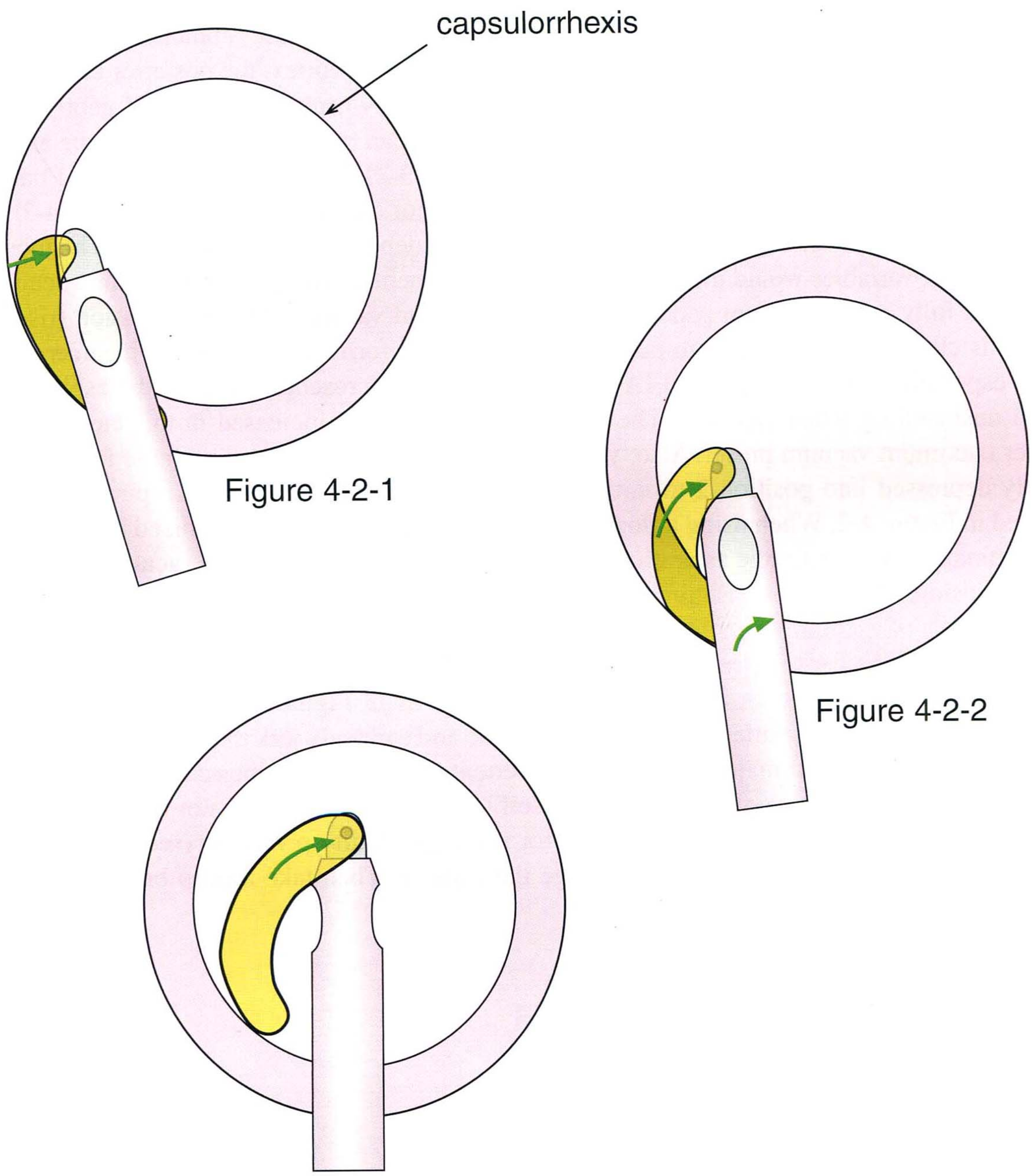


FIGURE 4-2

IA Port Turned Posteriorly

This is a technique that is often helpful for removing cortex at the subincisional position with the straight tip. As long as the aspiration port is occluded with cortex, the posterior capsule is safe (Figure 4-3-1). However, if this occluded cortex is suddenly aspirated instead of gently engaged and pulled as in the previous page, the posterior capsule can be directly exposed to the aspiration port's reestablished flow and potential surge (Figure 4-3-2). A characteristic star fold pattern is produced when the IA tip aspirates and grabs the posterior capsule, as shown in Figure 4-3-3. The probability of posterior capsule rupture in this situation depends on several factors. The most dangerous set of variables would include a vacuum pump machine with a high maximum vacuum preset and a fully depressed foot pedal. The rapid transfer of vacuum with tip occlusion (rise time), which is characteristic of vacuum pumps, would likely deform and rupture the incarcerated capsule, especially if utilizing a metal IA tip that may have microscopic burrs at the aspiration port from mishandling when cleaning. The safety margin could be increased in this case by using a lower maximum vacuum preset. Also, you could utilize linear IA control with the foot pedal only partly depressed into position 2 to initially engage cortex without abruptly aspirating it, as discussed in Figure 4-2. When using a flow pump machine, safety can be maximized by using a slower commanded flow rate; the aspiration line would not have any significant vacuum preload without occlusion, and the slow rise time would allow the maximum time for you to react before dangerous levels of vacuum were obtained. Finally, the use of a silicone IA tip (Figure 1-67) precludes the possibility of a capsule tear due to a metallic burr that is possible with a metal IA tip.

When confronted with a capsular star fold such as in Figure 4-3-3, you can be virtually assured of tearing the capsule or zonules if you panic and suddenly jerk the tip away while the capsule is engaged. The vast majority of these inadvertent capsular aspirations can be safely dealt with as long as you do not move the tip. Train yourself to react to this situation not with your hands but with your foot; go immediately to position 1 for venting of built-up vacuum (see Figures 1-15 and 1-46) or even to reflux position to disengage the capsule. Then take a deep breath and let your pulse return to normal.

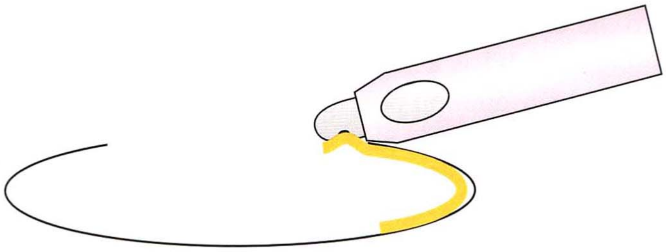


Figure 4-3-1

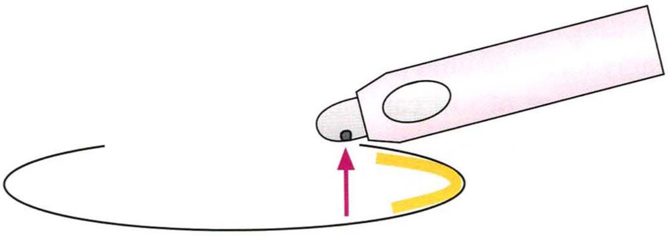


Figure 4-3-2

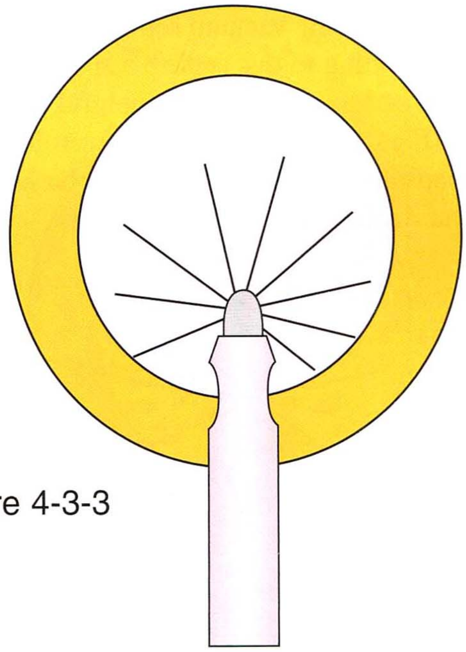


Figure 4-3-3

FIGURE 4-3

Capsule Vacuum

As opposed to the alarmingly large capsular star folds in Figure 4-3-3, the small, localized star-fold pattern in Figure 4-4-1 is a normal and appropriate visual feedback for capsule polishing by vacuuming with the IA aspiration port turned posteriorly, a step shown by Dr. David Apple to significantly reduce the incidence of postoperative posterior capsule opacification by removing residual lens epithelial cells. In order to protect the delicate posterior capsule, very low parameters are used, typically 5 cc/min for flow and 5 mm Hg vacuum (either a limit with a flow pump or commanded with a vacuum pump). The IA tip is gently drawn over the posterior capsule surface (either in a raster or a spiral pattern) with the aspiration port turned posteriorly as shown, with the star-fold pattern following the aspiration port as it moves. The safety of this step has been considerably enhanced with the introduction of silicone IA tips (Alcon and MicroSurgical Technology) that preclude the possibility of a sharp metallic nick or burr that could rupture the capsule even at these gentle parameter settings.

If the surgeon observes an alarmingly large star-fold pattern like that seen with high parameter settings in Figure 4-3-3, but in the presence of low capsule vacuum parameters as outlined above, then zonular integrity is likely compromised (Figure 4-4-2). The consequent lack of capsular support allows the posterior capsule to be more strongly aspirated and deformed even with the gentle capsule vacuum settings of 5 cc per minute flow and 5 mm Hg vacuum. Excessive capsule vacuuming in this setting can potentially disinsert even more zonules. A capsule tension ring (Ophtec or Morcher) is often helpful in these cases, typically changing the star-fold pattern from that in Figure 4-4-2 back to that seen in Figure 4-4-1 immediately upon placement of the device. The capsule tension ring can also be helpful in inhibiting vitreous prolapse through an area of zonular dehiscence.

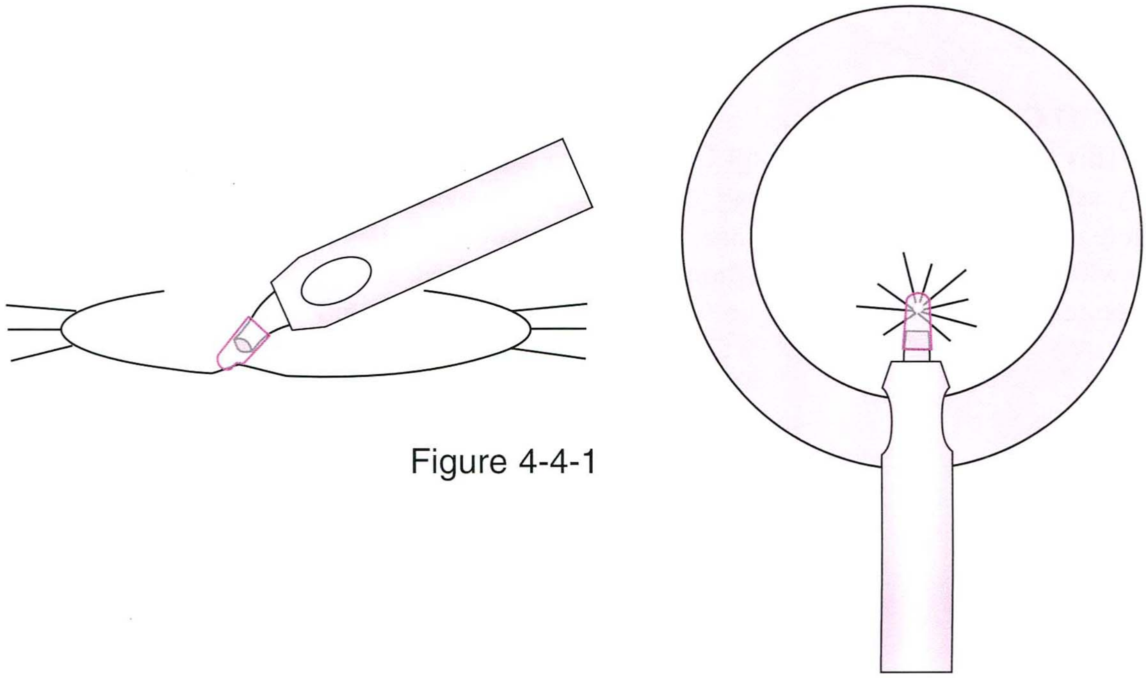


Figure 4-4-1

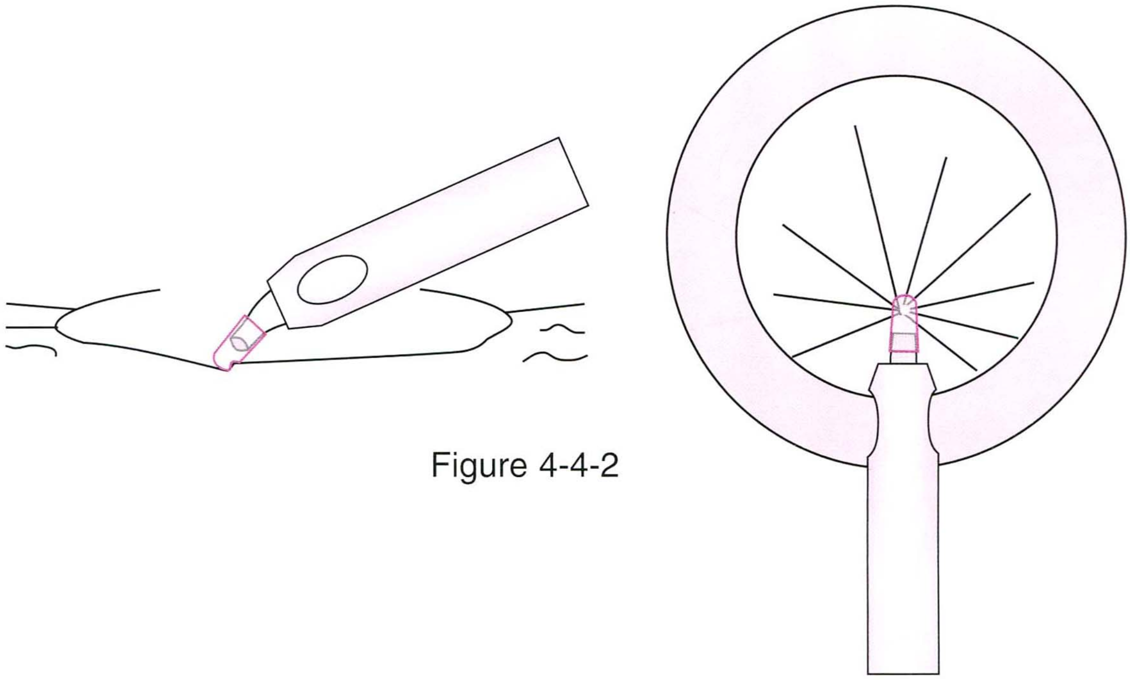


Figure 4-4-2

FIGURE 4-4

Manual Cortical Removal

A 27 Ga. angled or J-shaped cannula can be used on an irrigating syringe as shown in Figure 4-5. This technique is often helpful for tenacious subincisional cortex. The goal is not to necessarily aspirate the cortex completely but rather to engage it and peel it away from the capsule, pulling it to the center of the iris plane. At this point you can easily remove it by replacing the cannula with the IA tip with the aspiration port safely turned superiorly; the now free-floating cortex will be readily attracted to the aspiration port even when using moderate flow rates.

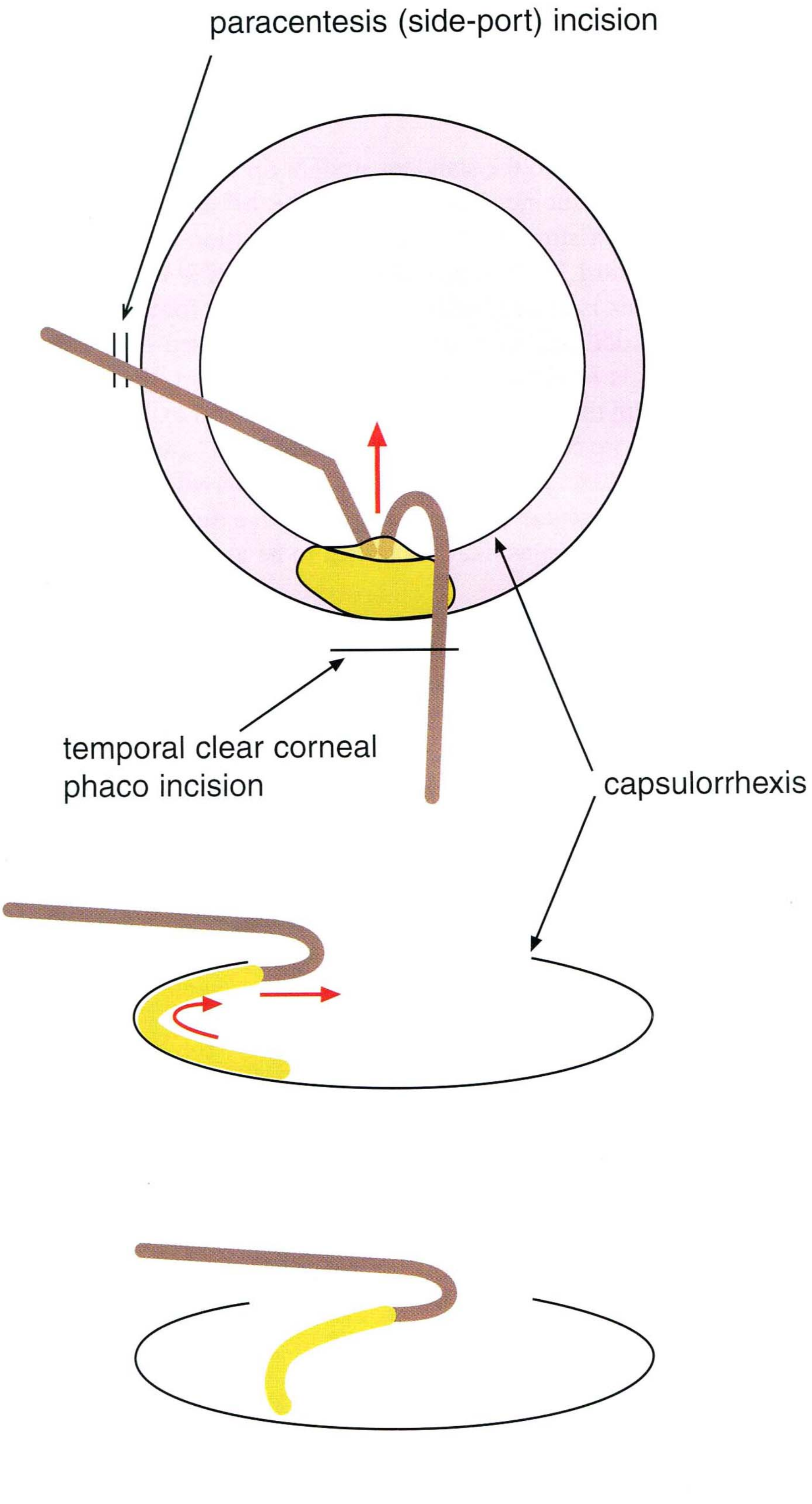

paracentesis (side-port) incision
temporal clear corneal
phaco incision
capsulorrhexis

FIGURE 4-5

90° and 45° IA Tips

These tips provide alternatives to the standard straight tip when you encounter cortex in difficult positions, particularly at the subincisional location. The 90° tip has several advantages at this position. The vacuum pulls most strongly in a peripheral direction as indicated by the arrow in Figure 4-6-1. Therefore, the most likely material to be aspirated is the cortex, not the capsule. Furthermore, the anterior cortex is more readily engaged, allowing for an efficient peeling motion as illustrated in Figure 4-5. Additional capsule protection is provided by the fact that the part of the tip that contacts the capsule is 90° away from the aspiration port, thereby physically holding the posterior capsule away from the port. Contrast this configuration to the 45° tip shown in Figure 4-6-2. Note how the part of the tip contacting the capsule is only 45° away from the aspiration port; the capsule is therefore more vulnerable to inadvertent aspiration with this tip relative to the 90° tip configuration. Similarly, the vacuum pulls most strongly in a direction 45° posteriorly as indicated by the arrow; the capsule is just as likely as cortex to be aspirated in this illustration.

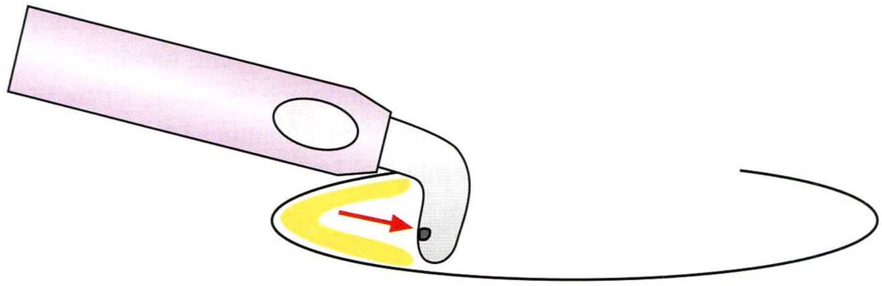


Figure 4-6-1

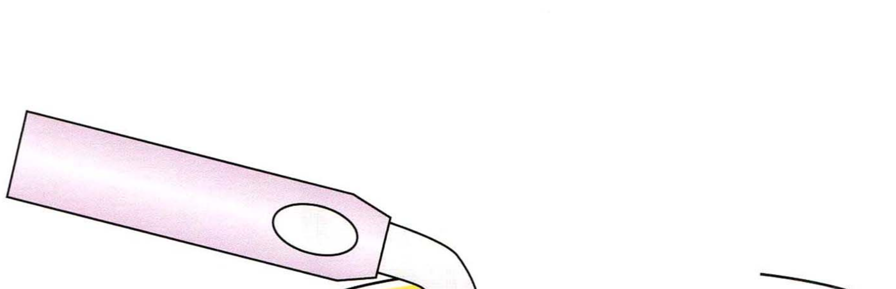


Figure 4-6-2

FIGURE 4-6

Bimanual Irrigation and Aspiration

Similar to the bimanual phaco described in Figure 1-2, bimanual IA uses separate irrigation and aspiration handpieces as opposed to a single aspirating handpiece with a coaxial irrigation sleeve. By utilizing two separate paracentesis ports for the two handpieces, subincisional cortex may be reached easily as shown in Figure 4-7, and if necessary, the handpieces can be switched between the two incision sites to allow the aspiration handpiece to access virtually anywhere within the capsule. If bimanual phaco had been utilized, then bimanual IA may be used as shown in Figure 4-7. If traditional phaco had been used, bimanual IA incisions are typically made about 30° to both sides of the main phaco incision.

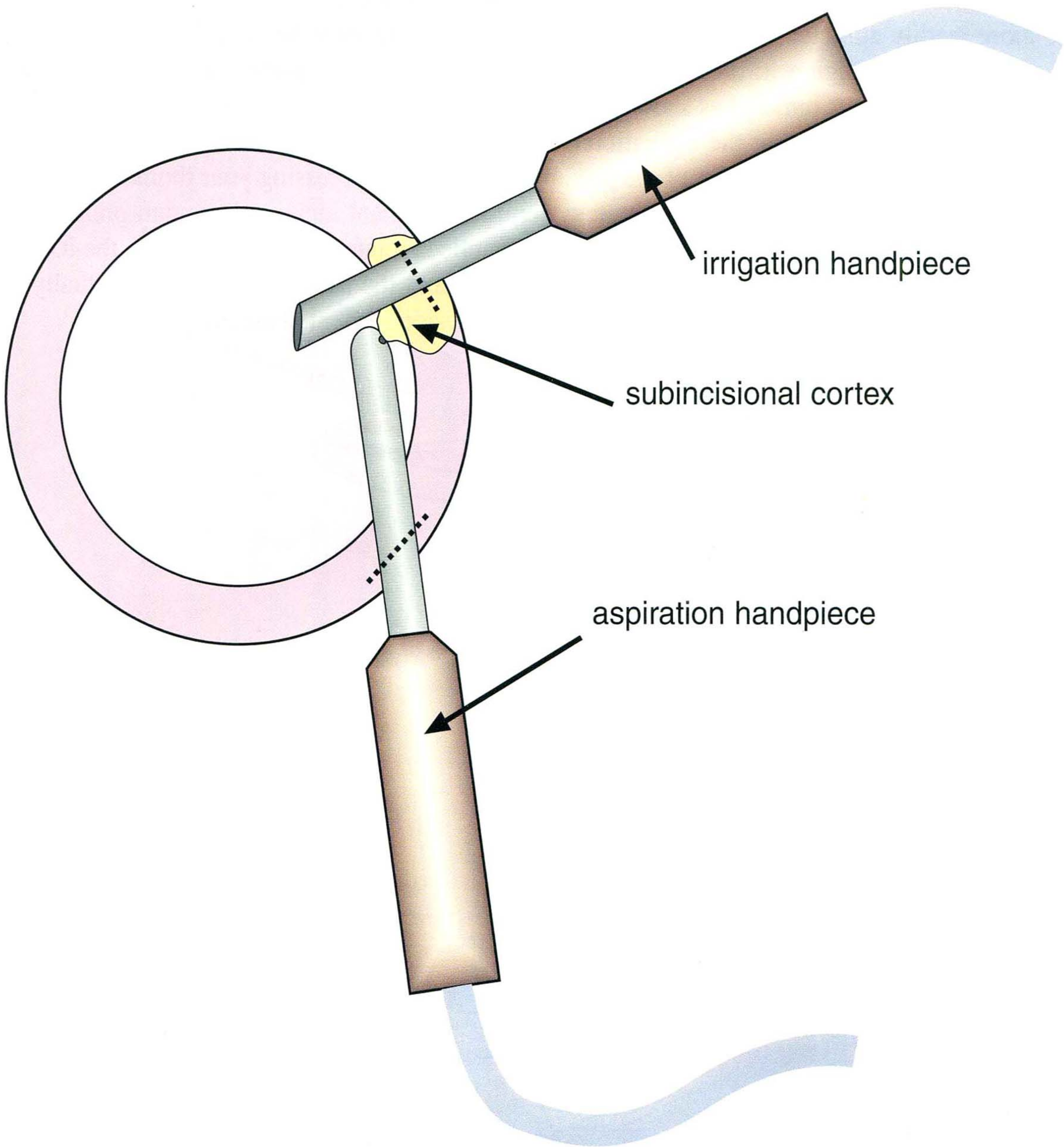

irrigation handpiece
subincisional cortex
aspiration handpiece

FIGURE 4-7

Using the IOL to Help Remove Cortex

The IOL, or intraocular lens, can be used to help remove residual cortex in two ways. First, rotation of the lens in the bag utilizes the haptics to help dislodge peripheral cortex so that it can be more readily attracted to the IA tip. Of course, the haptic must be rotated past the cortex in question after dislodging it; otherwise the haptic might entrap the cortex against the peripheral capsule and inhibit its removal as shown in Figure 4-8. This figure also illustrates the use of a tip-down configuration. Having the aspiration port in such close approximation to the IOL surface effectively decreases the diameter of the port, much the same as pressing your thumb over the end of a garden hose creates a higher pressure system; the resultant increased vacuum preload more readily aspirates any engaged cortex after the IOL haptic is rotated away. In addition, the IOL provides a physical barrier between the posterior capsule and the aspiration port that virtually precludes posterior capsule incarceration even with a posteriorly oriented aspiration port.

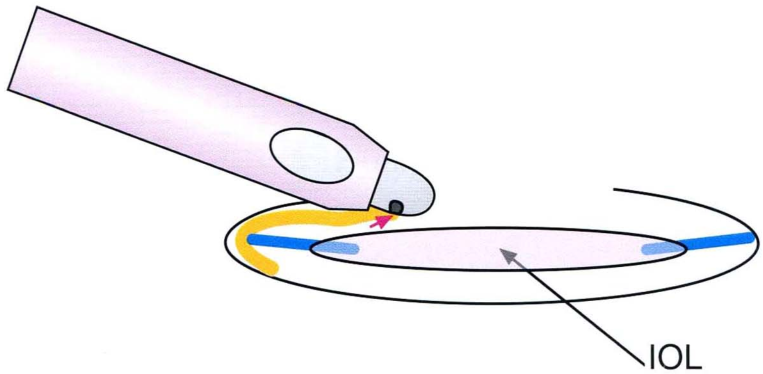


FIGURE 4-8

Epinuclear Mobilization via Cortical Pulley

The epinucleus occasionally does not have sufficient structural integrity to allow flipping as a complete bowl, and the residual subincisional portion is sometimes difficult to maneuver to a contraincisional location for aspiration. In these cases, the subincisional cortex may be used as a pulley to mobilize the epinucleus as shown in Figure 4-9. The parameter logic discussed in Figures 2-21 and 4-2 is used to allow a firm grip of the cortex so that movement of the IA tip peels the cortex away from the capsule along with the epinucleus. Excessive vacuum or abrupt movement of the IA tip will tend to tear the cortex, thereby defeating its use as a pulley. Once centrally mobilized away from the capsule, the epinucleus can generally be safely aspirated with the IA tip, although occasionally the phaco tip may be reinserted for this purpose.

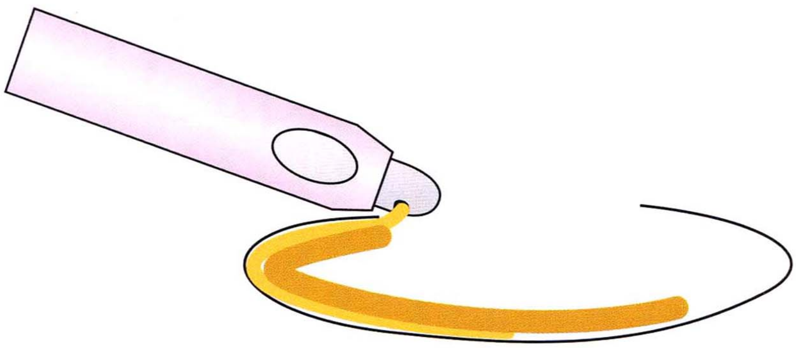


Figure 4-9-1

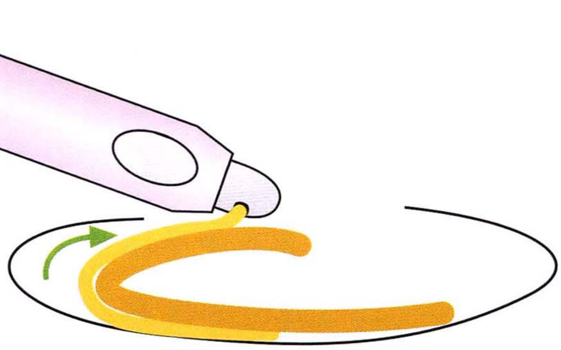


Figure 4-9-2

FIGURE 4-9

SECTION FIVE

Physics of Capsulorrhexis

Stress and Strain

The Continuous Curvilinear Capsulorrhexis (CCC) was independently developed by Drs. Howard Gimbel and Thomas Neuhann; it is universally acknowledged as one of the fundamental elements of modern phaco surgical techniques. An understanding of the dynamics of creating a capsulorrhexis begins with an overview of material analysis. Figure 5-1-1 is a strip of material without any forces acting on it; the interdigitated central portion represents the intermolecular attractions at this location. Figure 5-1-2 depicts the material with very mild force applied as indicated by the arrows; **stress** is the force divided by the cross-sectional area where the force is being applied (the central interdigitated area in this case). In Figure 5-1-3, the stress has increased (bigger arrows) so that the material begins to deform; note the stretching at the center. **Strain** is defined as the change in length of a deformed material divided by its original length. If strain is increased just beyond a material's elastic limit, the material will be permanently deformed even after stress is discontinued. As strain increases further beyond the **elastic limit**, stress usually initially increases slightly but then decreases as the material's breaking point is approached. When this point is reached, the intermolecular bonds are broken and the material tears apart. Note the slightly smaller force arrows in Figure 5-1-4 relative to those in Figure 5-1-3; these smaller arrows represent the force required just prior to the breaking point.

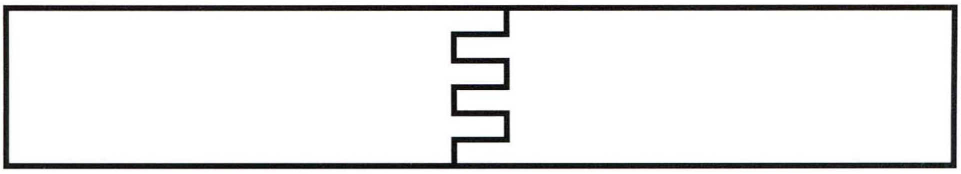


Figure 5-1-1

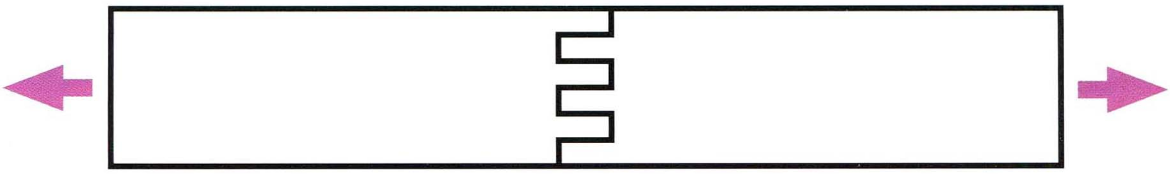


Figure 5-1-2

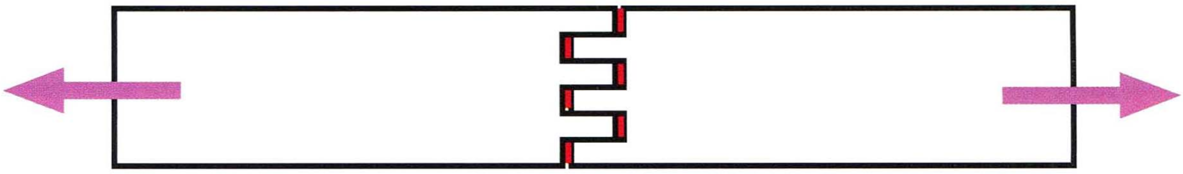


Figure 5-1-3

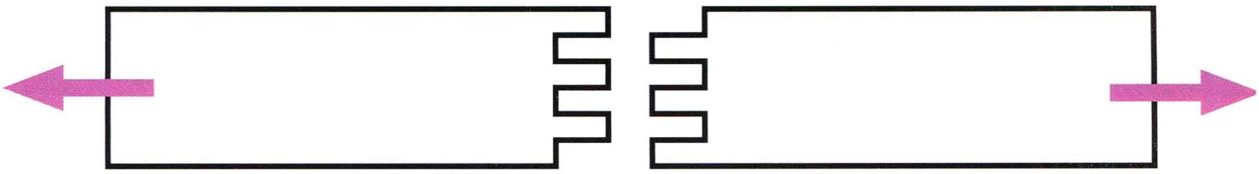


Figure 5-1-4

FIGURE 5-1

Shear vs Rip

Figure 5-2-1 illustrates **shearing** principles. Area x remains stationary while area y is pulled from point a to point b in order to tear this material from point A to point B. All of the pulling force is concentrated at the point of tearing and is in the same direction as the tear. Even though area y may still be engaged by a cystotome or forceps at point b, no further tearing will occur as long as the instrument is not moved. Contrast this with the **ripping** schematic shown in Figure 5-2-2, where area x is again stationary and the material is engaged with an instrument at the blue dot and pulled with vector force t (note the arrows pointing left, which represent the counterforce caused by the left side of the material being stationary). Although no tearing occurs while y is pulled from a toward b, stress and strain in the material progressively increase. When point b is reached, the strain passes the material's breaking point and ripping begins in the direction noted by arrow E. Figure 5-2-2 depicts the material just as ripping begins. Point A has just ripped apart. Point B is undergoing strain. Point C has some stress without any deformation, and point D has no forces acting on it. Note the changes in the points when the rip reaches point B (Figure 5-2-3). Point C, which previously had stress without deformation, now has strain. Point D, which formerly had no forces acting on it, now has stress. The rip will tend to propagate in this fashion as long as area y is held firmly at point b, even though it is not being moved any further. Recall that the stress required at the breaking point is less than that required to reach the breaking point; the surplus force fuels the tear's propagation.

Therefore, ripping the capsule is less desirable than shearing for two reasons. First, the tear tends to uncontrollably extend when ripping even when the grasping instrument is held stationary. Second, more force is generally needed to begin a tear with ripping as opposed to shearing because the force is distributed over a larger area with ripping (ie, at points A, B, and C in 5-2-2) relative to the concentration of force just at the point of tearing with shearing (point A in Figure 5-2-1). Moreover, only a component vector (t_1) of the pulling force pulls the material apart with ripping while the residual force (t_2) serves to direct the rip in direction E; contrast this to the efficiency in shearing of all of the pulling force being utilized in the direction of the tear.

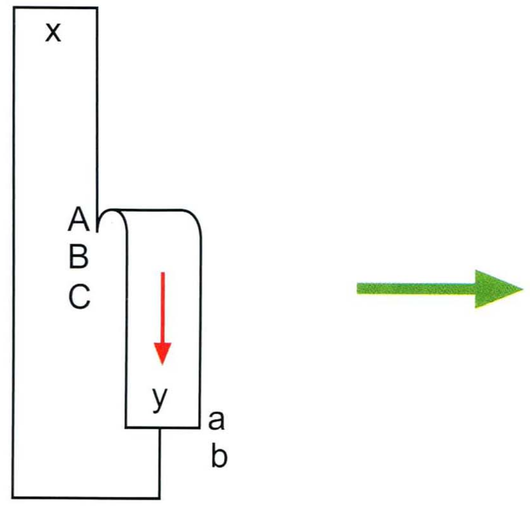


Figure 5-2-1

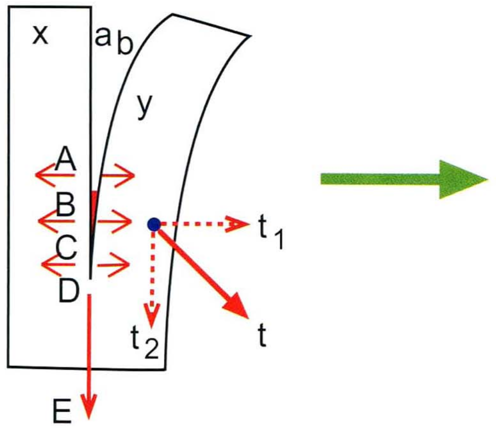


Figure 5-2-2

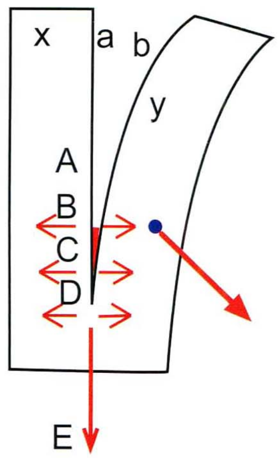


Figure 5-2-3

FIGURE 5-2

Capsulorrhexis with Shearing

Capsulorrhexis often begins with the formation of a flap as in Figure 5-3-1. The cystotome enters at point 1 and then proceeds to point 4 using either small, connecting can-opener bites or a side-cutting cystotome. At point 4, the cystotome is pulled in the direction of the blue arrow to create a capsular flap, which is then folded over to lay on top of intact anterior capsule as shown. The flap is engaged with a cystotome or capsular forceps at the blue dot at point y and pulled in the direction of the curved green arrow. When using a cystotome, press only hard enough to engage and move the flap; too much force may penetrate the flap, thus inadvertently cutting the intact capsule beneath as well as retarding progression of the flap because of resistance created by engaged cortex. Note that point y is somewhat inside of the peripheral edge of the flap in order to provide a safety margin against the cystotome slipping peripherally off of the flap and damaging intact capsule.

Figure 5-3-2 shows further progress. Notice the symmetry around point a. The flap is a mirror image of the area of capsulorrhexis performed thus far; furthermore, it provides a template showing where the capsulorrhexis will proceed. The flap is grasped at point y and pulled in a curvilinear fashion as shown. Figure 5-3-3 shows the capsulorrhexis one third completed. Notice how the point of instrument engagement (y) is adjusted to stay 2 to 3 clock hours away from the point of shearing. If the instrument were instead placed closer, such as point z, an artifactual stress line (green dashed line) could be created which would compromise the predictability of the direction of shear propagation.

Compare the flap positions in Figures 5-3-2 and 5-3-4. Note the loss of symmetry around point a in Figure 5-3-4, which has more of a bullet-shaped configuration relative to the continuous mirror-image curve through point a in Figure 5-3-2. The reason for the difference is that the flap has not been spread out flat in Figure 5-3-4 (note the folds in the flap). If this flap is engaged at point y and pulled as shown, the capsulorrhexis shear will proceed but with a smaller radius than in Figure 5-3-2. Sometimes you may elect to purposely change the size of the capsulorrhexis in this manner, but be aware that only gradual changes in curvature are practical when utilizing shearing. If the flap is pulled to make an even smaller capsulorrhexis than Figure 5-3-4 (ie, a more pointed bullet shape at point a), a distortion is induced at point a which converts the shear to a modified rip which often propagates peripherally. Abrupt changes in the direction of the tear are best accomplished by a planned ripping maneuver as shown in Figure 5-4.

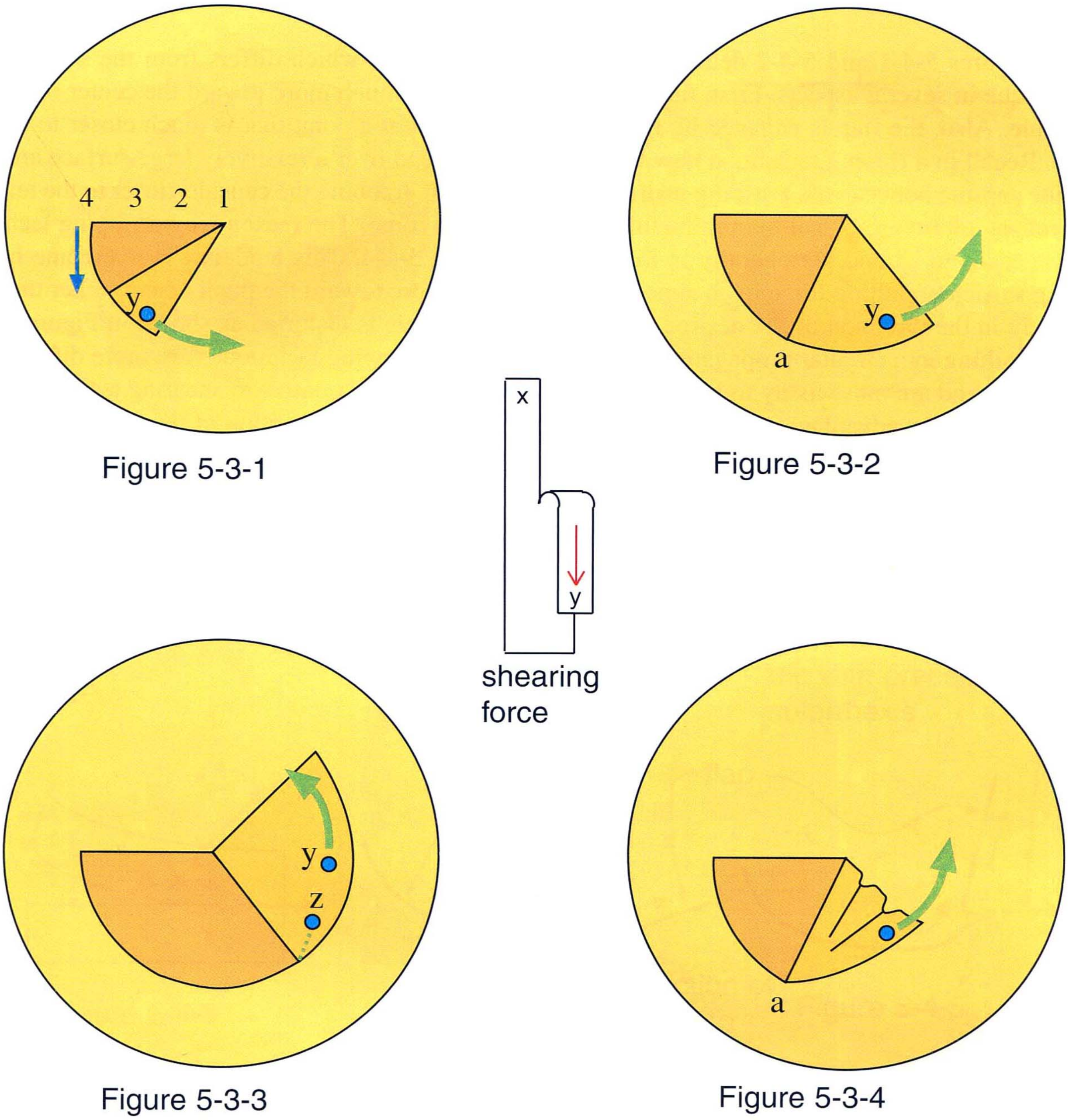

4 3 2 1
y
Figure 5-3-1
y
a
Figure 5-3-2
x
y
shearing force
y
z
Figure 5-3-3
a
Figure 5-3-4

Figure 5-3

Capsulorrhexis with Ripping

Figures 5-4-1 and 5-4-2 demonstrate a ripping technique, which differs from the shearing technique in several aspects. First, the direction of pulling is much more toward the center of the capsule. Also, the flap is engaged by the pulling instrument at a point that is much closer to the tear. Recall in a ripping technique how tearing force is spread over a relatively large surface area of the capsule between the grasping instrument and the tear; grabbing the capsule closer to the tear therefore improves control by minimizing any extraneous force. The reason why a ripping technique tends to extend peripherally is illustrated in Figure 5-4-4. This tendency is overcome by using sufficient pulling force in an appropriate direction (more toward the pupil center rather than directly in the direction of the desired tear) so that the capsule is distorted as shown in Figure 5-4-5, resulting in a circular propagation of the tear. Although ripping techniques are more difficult to control and are more likely to inadvertently extend peripherally relative to shearing techniques, they do have the advantage of enabling more abrupt changes in the direction of the tear.

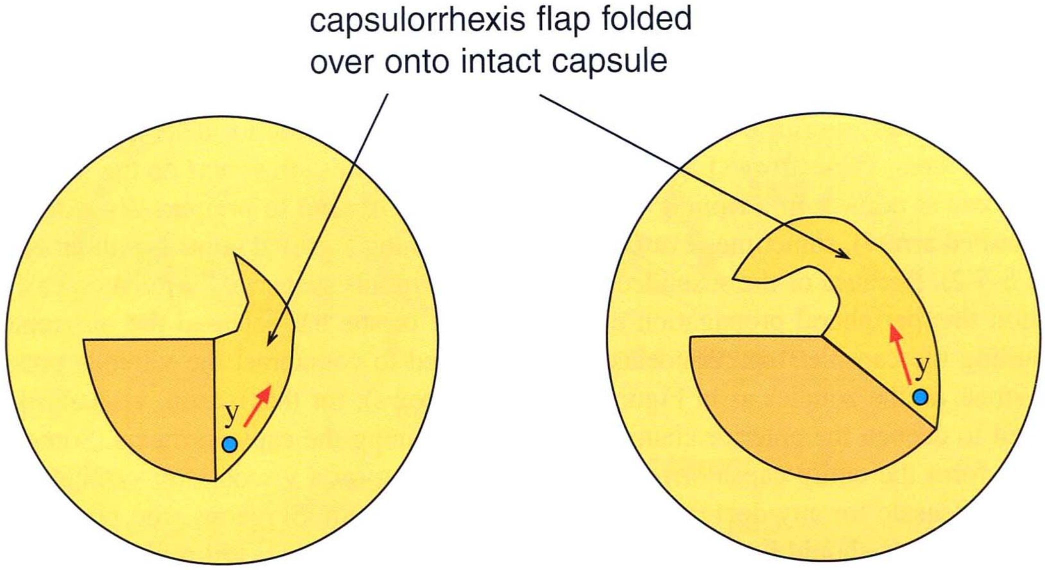


Figure 5-4-1

Figure 5-4-2

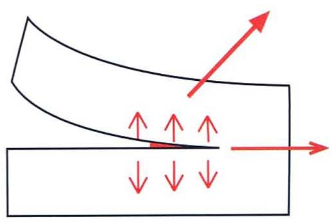


Figure 5-4-3

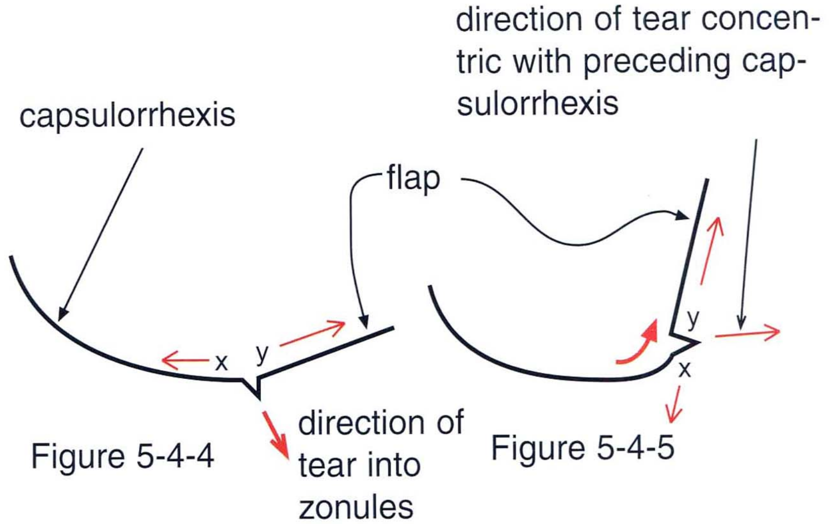


Figure 5-4-4

Figure 5-4-5

FIGURE 5-4

Maintaining Chamber Depth

A shallow anterior chamber usually indicates that vitreous pressure (red arrow in Figure 5-5-1) is greater than anterior chamber pressure, resulting in the anterior displacement of the lens with zonular stress (blue arrows) as shown in Figure 5-5-1. This stress acts on the site of a capsulorrhexis tear at point x in a ripping configuration that will tend to peripherally extend the tear (green dashed arrow), sometimes even with just maintaining a grip at point y without any pulling (Figure 5-5-2). Because of the sustained zonular forces in this scenario, the surgeon can watch in frustration this peripheral propagation even though he or she has released the instrument grasp from pulling the capsule flap. Viscoelastic may be used to counteract the vitreous pressure and relieve stress on the zonules as in Figure 5-5-3 (red arrows); for this reason, viscoelastic is typically used to deepen the anterior chamber prior to beginning the capsulorrhexis. Some surgeons like to perform the entire capsulorrhexis with a cystotome on a viscoelastic syringe in order to readily compensate for any decrease in anterior chamber depth. Surgeons who prefer using capsulorrhexis forceps should have viscoelastic readily available for injection through the side-port paracentesis incision in case of shallowing of the anterior chamber.

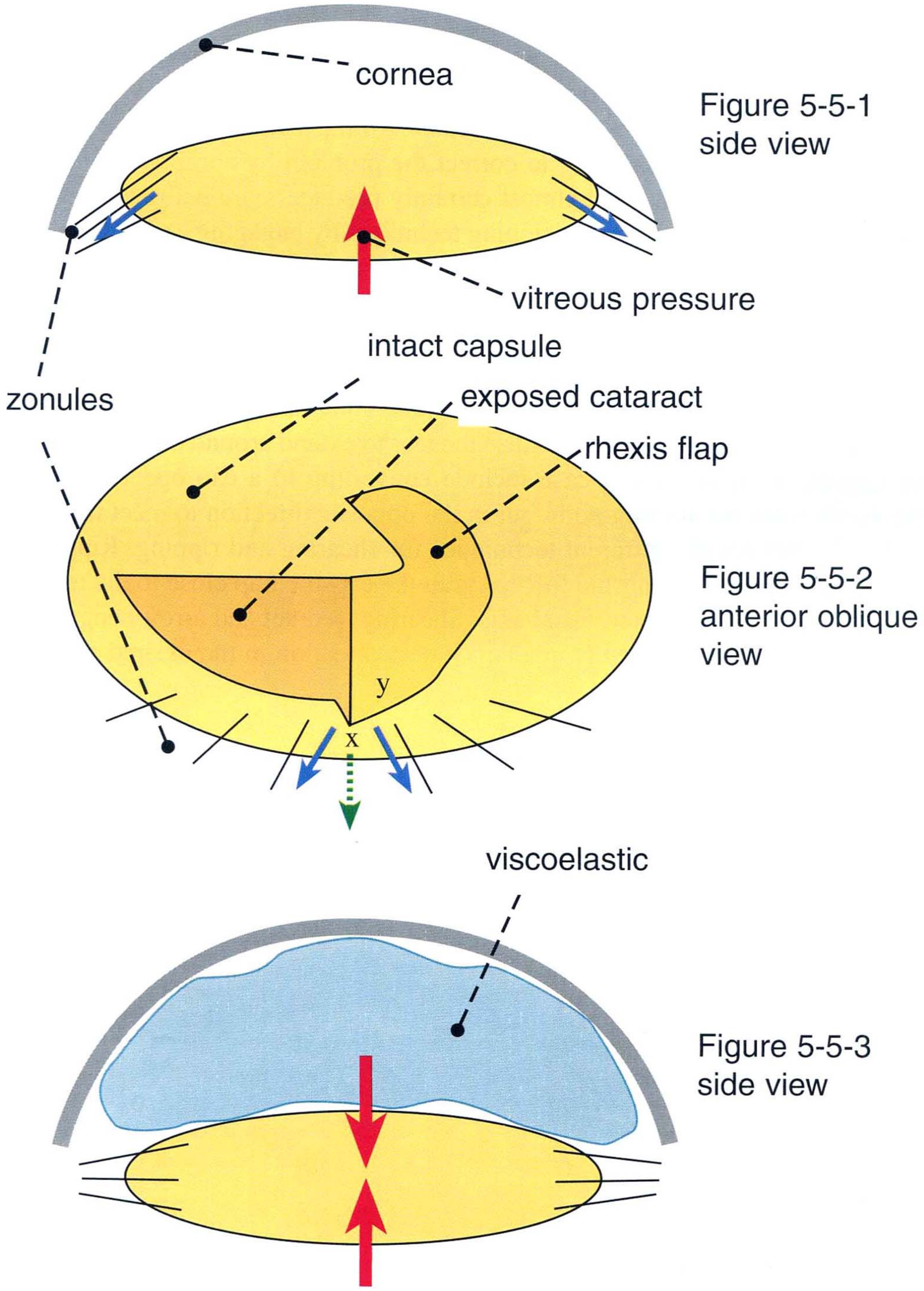

cornea
Figure 5-5-1
side view
vitreous pressure
intact capsule
zonules
exposed cataract
rhexis flap
Figure 5-5-2
anterior oblique
view
y
x
viscoelastic
Figure 5-5-3
side view

FIGURE 5-5

Combining Techniques

Figure 5-6-1 shows a capsulorrhexis proceeding smoothly using a shearing technique; note the smooth mirror-image symmetry around point a. In Figure 5-6-2, a relative shallowing of the anterior chamber contributed to the peripheral extension of the tear. Point b is spear/bullet-shaped instead of smooth and round. Attempting to correct the problem by abruptly changing direction with a shear technique (red arrow) will almost certainly produce more peripheral extension. The better option in this case is to convert to a ripping technique by engaging and pulling as indicated by the blue dot and arrow; viscoelastic is used to reinflate the chamber prior to executing the ripping maneuver. Once a desired configuration is again obtained, you can convert back to a shear technique as illustrated in Figure 5-6-3.

In these situations, the surgeon must be aware if the capsulorrhexis tear has extended into the zonules (typically starting around 8 mm diameter on the anterior capsule). In these cases, excessive pulling (as in a ripping maneuver) can cause the tear to extend around the capsule equator into the posterior capsule. Options in this case include converting to a can opener capsulotomy vs restarting the rhexis from the starting point but in the opposite direction to meet the extension.

Figure 5-6-2 reiterates the different techniques for shearing and ripping. Ripping (blue dot and arrow) has the cystotome or capsule forceps grab the capsule flap close to the tear and pull in a straight direction close to the center visual axis. Shearing (red dot and arrow) engages the flap 2 or 3 clock hours from the tear and pulls in a curvilinear direction in the desired direction of tear propagation.

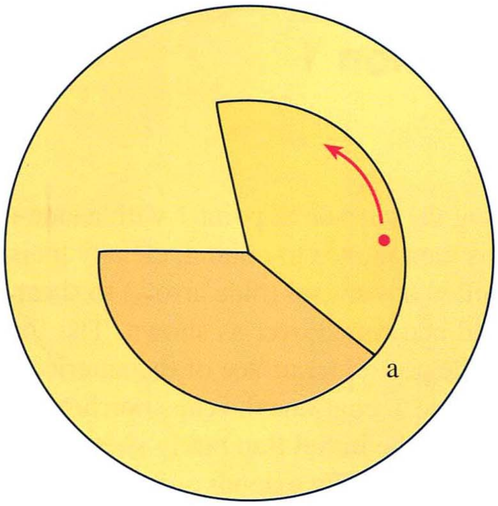


Figure 5-6-1

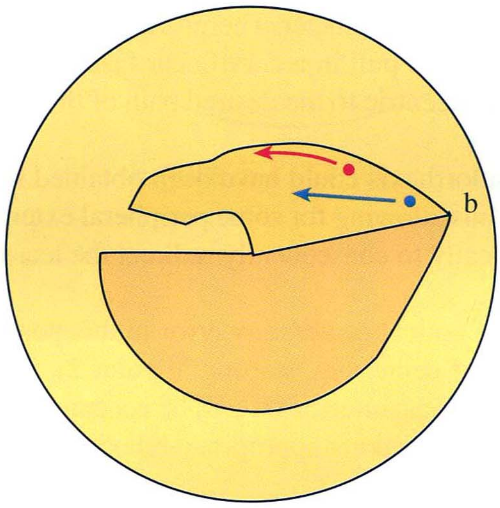


Figure 5-6-2

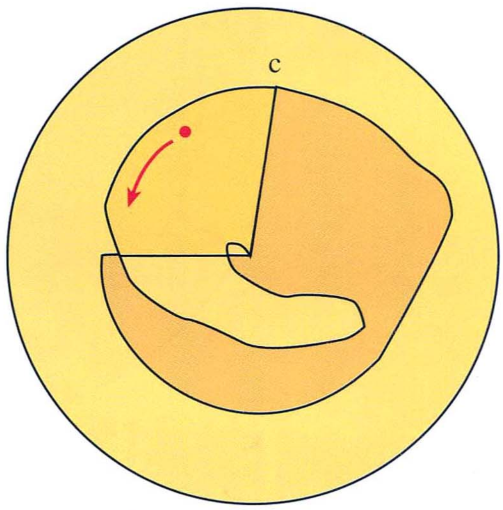


Figure 5-6-3

FIGURE 5-6

Capsulorrhexis Initiation 1

One way to begin the capsulorrhexis is by puncturing the capsule at point 1 with a side-cutting cystotome on a viscoelastic syringe. The cystotome is then moved to point 4, cleanly incising the capsule as it is moved. At point 4, the cystotome is pulled downward (blue arrow) to shear the capsule at this point so that a capsular flap can be created and rolled over as shown. The flap is engaged with forceps or cystotome at point y (originally the posterior surface of the anterior capsule) and pulled in the direction of the curvilinear green arrow to continue the capsulorrhexis with a shearing technique. One problem with this technique is that the initial flap rarely shears exactly in the direction of the blue arrow as shown in Figure 5-7-1. It usually extends somewhat peripherally as shown in Figure 5-7-2. The remedy for this problem is to simply allow for it; point 4 should be central to your desired final diameter. Therefore, when given the configuration in Figure 5-7-2, engage the flap at point y and pull in a curvilinear fashion as depicted by the green arrow. Note that this curved arrow is concentric to the desired path of the capsulorrhexis, which is depicted by the red arrow.

A smaller diameter capsulorrhexis could have been obtained in Figure 5-7-2 by either starting the flap closer to point 3 (thus allowing for some peripheral extension) or pulling the flap more centrally rather than concentrically to consequently redirect the tear more centrally (see Figure 5-3-4).

Note that point 1 is in the optical center; any error in this positioning should be to the right of center. If you err to the left of center (eg, starting at point 2), the resultant flap radius will be constrained such that the resultant capsulorrhexis will be eccentric (to the left) and too small. This error is of course easily rectified by making appropriate relaxing incisions to extend the flap radius to or beyond the center.

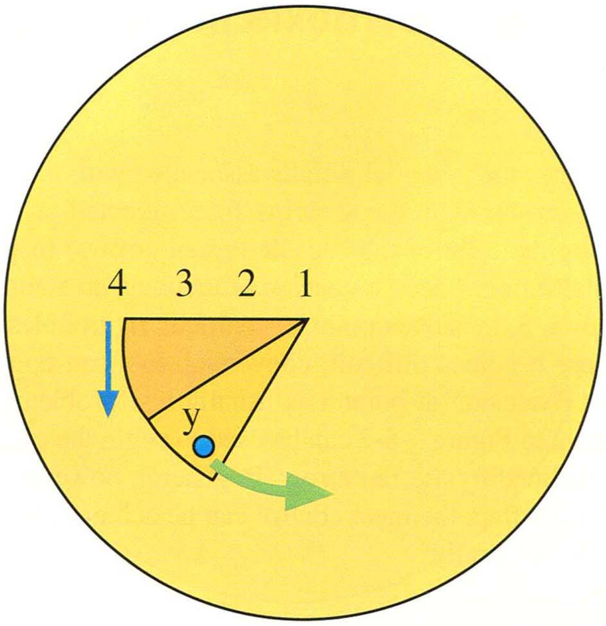


Figure 5-7-1

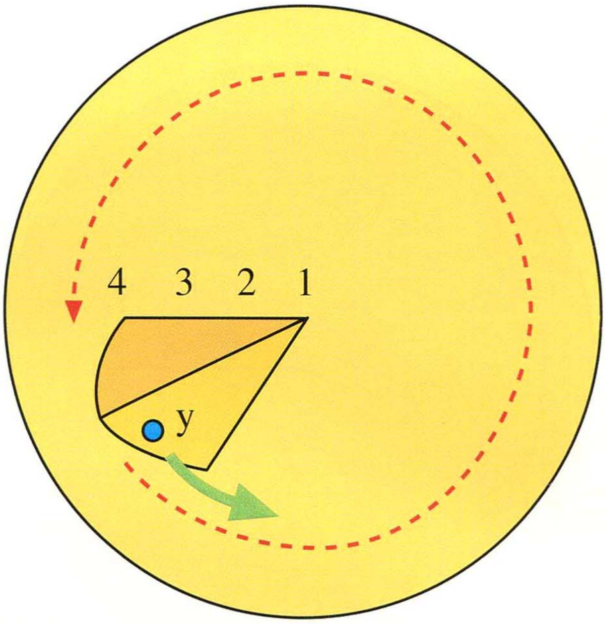


Figure 5-7-2

FIGURE 5-7

Capsulorrhexis Initiation 2

Figure 5-8-1 illustrates the potential pitfalls associated with pulling the capsule at a point central to point 4 (blue arrow). With the shearing force directed as shown by the blue arrow, force is transmitted along the edge of the capsule (green arrows) to both ends of the incision, with consequent potential for peripheral extension of the incision at either end by ripping forces as shown by the red arrows. Extension at point 4 is particularly troublesome because if it extends into the zonules, recovery becomes difficult; conversion to a can-opener capsulotomy is often required in these cases. Extension at point 1 is usually less problematic. In fact, the possible extension at point 1 shown in Figure 5-8-2 can be used to begin the capsulorrhexis by clockwise rotation of the flap as outlined by the red arrow. In general, however, if you wish to shear the capsule at point 4 to begin a flap, the most control can be achieved by pulling the capsule right at point 4 rather than more centrally.

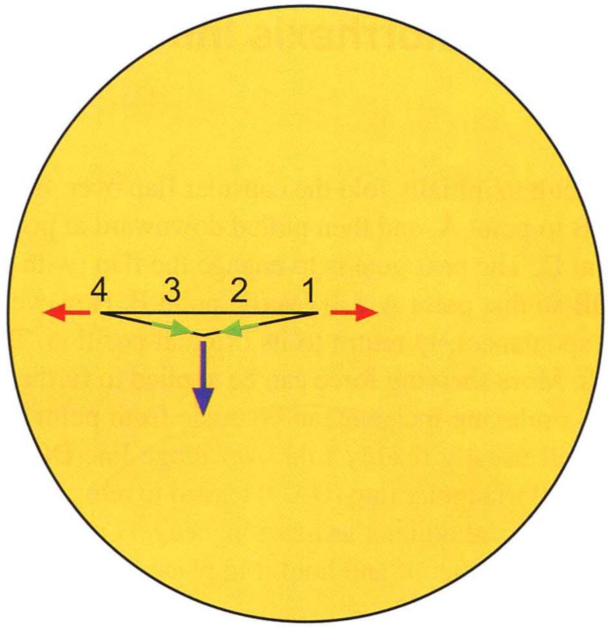


Figure 5-8-1

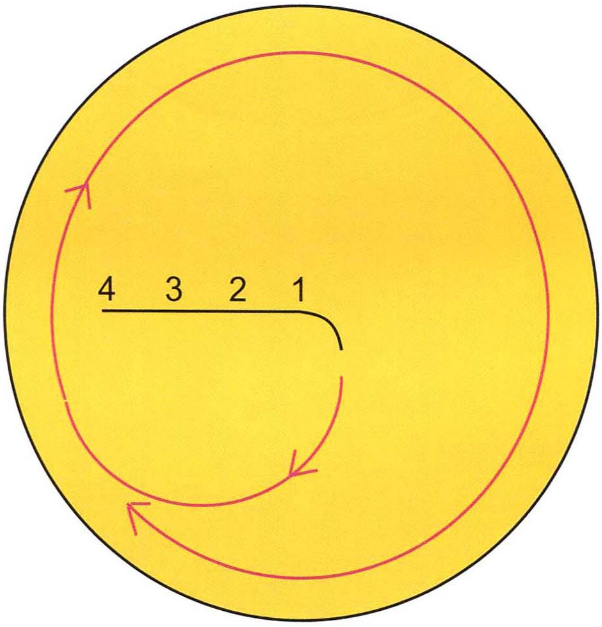


Figure 5-8-2

FIGURE 5-8

Capsulorrhexis Initiation 3

Sometimes it is difficult to initially fold the capsular flap over. In Figure 5-9, the capsule has been incised from point B to point A, and then pulled downward at point A to create the shearing tear from point A to point D. The next goal is to engage the flap (with cystotome or forceps) and fold it over hinge line DB so that point A will overlie point E. However, after thus positioning it, the flap will sometimes spontaneously return to its original position. This tendency can be overcome in a couple of ways. More shearing force can be applied to further extend the tear from A to beyond D. Alternatively, a relaxing incision can be made from point B to point C. The resultant U-shaped flap (CBAD) will usually readily fold over hinge line DC and stabilize in the folded position, whereas the original triangular flap (BAD) tended to return to its in vivo position because of constraint at point B. A helpful adjunct to these maneuvers is to inject additional viscoelastic over the folded flap in order to flatten it and hold it in place.

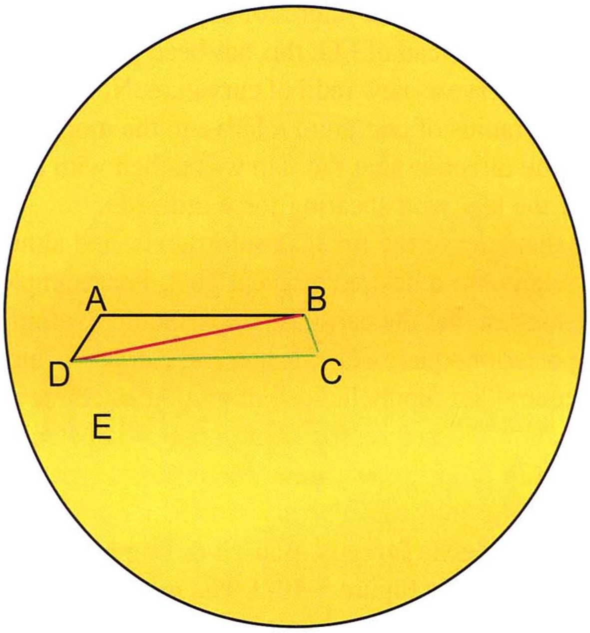


FIGURE 5-9

Capsulorrhexis Initiation 4

An alternate method for beginning the capsulorrhexis is shown in Figure 5-10-1. The capsule has been incised by a cystotome or pinched by a capsulorrhexis forceps at point A; the ensuing triangular flap is grasped at point B and drawn in the direction of the red arrow. Shearing forces are acting roughly equally at points C and D, resulting in a capsule strip with parallel sides. In Figure 5-10-2, the pulling motion has changed to a curvilinear direction (red arrow), which results in the strip changing direction by curving from F to G with point E acting as a central pivot point; the lines EF and EG are radii of curvature for this portion of the tear. At this point, AG can be used as a radius of curvature instead of EG; this has been performed in Figure 5-10-3 where AI and AG (from Figure 5-10-2) serve as new radii of curvature. Notice how the curvilinear red arrow in 5-10-3 reflects this larger radius of curvature relative to the more tightly curved arrow in 5-10-2; these arrows represent the direction that the flap was pulled with either a cystotome or forceps to control the direction of the tear with shearing force utilized.

Point G defines the diameter of the final capsulorrhexis, and although it can be estimated, it is helpful to measure it relative to a desired surgical goal. For example, Dr. Okihiro Nishi's and Dr. David Apple's work suggest that the capsulorrhexis should overlap the anterior surface of the IOL optic such that the posterior square edge, if present, can press into the posterior capsule and more effectively inhibit central lens epithelial cell migration and therefore reduce the incidence of posterior capsule opacification. Therefore, for a 6 mm optic diameter, a 5 mm capsulorrhexis will provide a 0.5 mm overlap. In order to determine the distance from the pupil edge that point G should be placed to achieve a 5 mm capsulorrhexis diameter, a capsule forceps with millimeter markings (eg, **Seibel capsulorrhexis forceps**, Bausch & Lomb Surgical, Rhein Medical) may be used to calibrate the size as shown in Figure 5-10-2. The instrument is placed such that the tip and the 5 mm mark are equidistant from the pupil edge (**purple arrows**), and this distance is used as the guideline for the distance from G to the pupil edge.

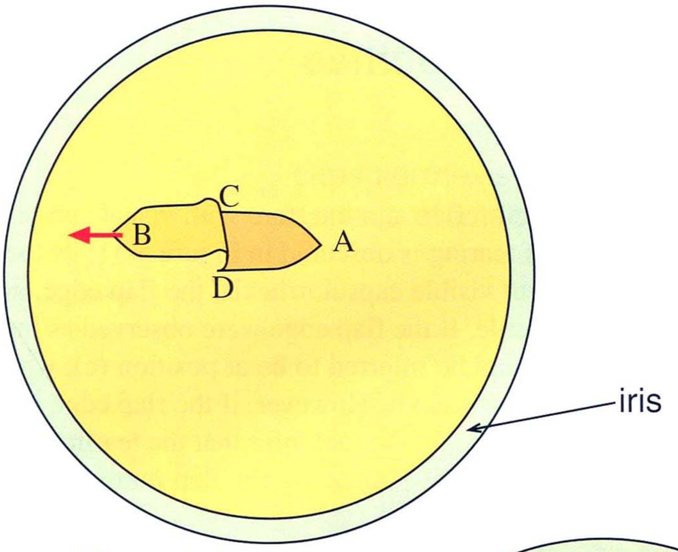


Figure 5-10-1

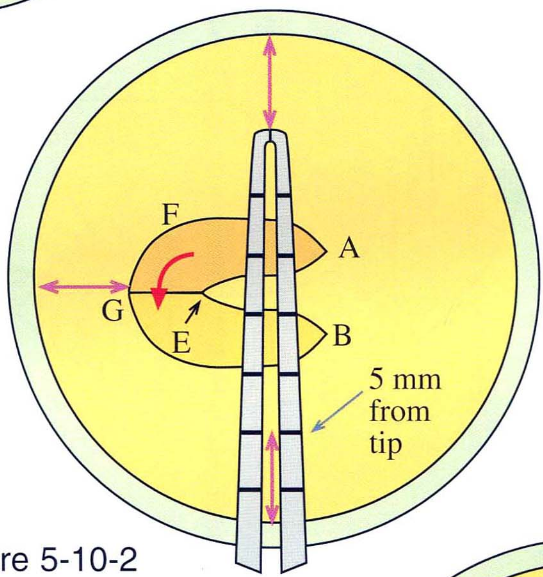


Figure 5-10-2

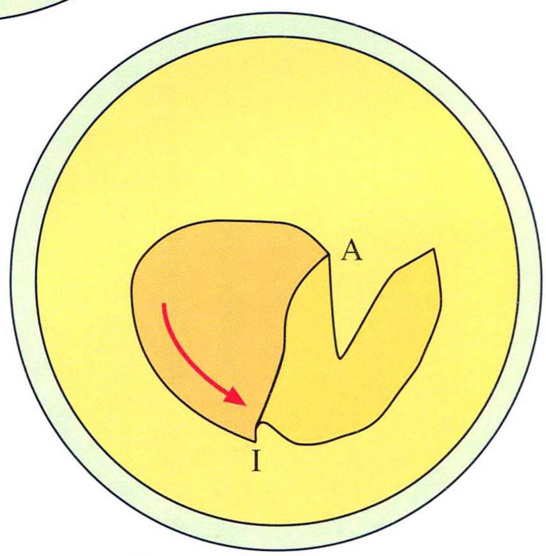


Figure 5-10-3

FIGURE 5-10

Anterior Cortical Opacities

Dense anterior cortical opacities can block the red reflex and interfere with visualization of the capsulorrhexis. However, even though the point of tearing is obscured in Figure 5-11, its location can be extrapolated (green lines) from the adjacent visible capsulorrhexis, the flap edge, and the line formed as the flap folds over on the intact capsule. If the flap edge were observed as indicated by the black line (a), then the point of tearing could be inferred to be at position (c), which would be consistent with the preceding section of capsulorrhexis. However, if the flap edge were visualized along the red line (b) instead of the black line (a), you could infer that the tearing point was too peripheral (d) and take appropriate measures, such as redirecting the flap more centrally or even converting to a ripping technique.

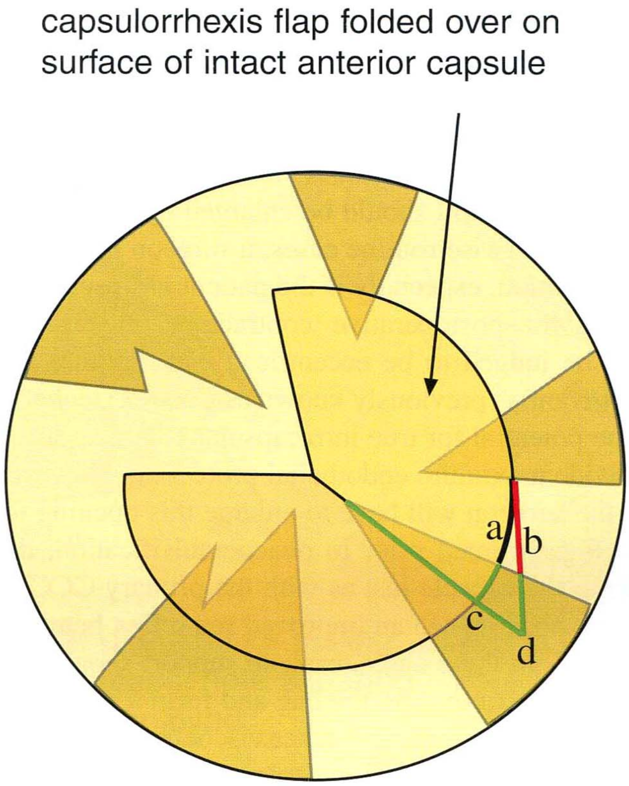

capsulorrhexis flap folded over on
surface of intact anterior capsule
a
b
c
d

FIGURE 5-11

Capsulorrhexis Enlargement

Several surgical situations may require an enlargement of a completed CCC. A poor red reflex might induce the surgeon to initially err on the side of too small a CCC rather than too large in order to avoid a possible extension into the zonules. (A capsule stain such as ICG or Vision Blue (DORC) can help tremendously in these cases.) A small pupil may also induce a small capsulorrhexis, although in these cases the pupil should be enlarged by stretching (per Dr. Luther Fry) or iris retraction hooks. Even in otherwise routine cases, a surgeon might simply judge a CCC to be too small prior to IOL implantation, especially if the patient has pseudoexfoliation syndrome and is therefore at greater risk for postoperative contracture of the CCC (capsule phimosis). Sometimes, the CCC may be judged to be eccentric. Finally, future technologies may require enlargement. For example, Avantix (previously known as Catarex) technology, as described by Dr. Richard Kratz, promises the potential for true intracapsular cataract removal through an eccentric 1.2 mm CCC; this will provide maximum endothelial protection. However, until an injectable gel IOL material is available, the surgeon will have to enlarge this opening to utilize current IOLs.

If CCC enlargement is performed prior to phacoemulsification, the intact crystalline lens provides structural support to the capsule just as with the primary CCC. However, CCC enlargement is often performed after phaco when an improved red reflex better delineates the actual size and shape of the primary CCC. In these cases, capsule support should be maximized as much as possible by the use of viscoelastic to expand the bag and form a pseudo-nucleus (Figure 5-12-4). In addition to filling the bag with viscoelastic, further viscoelastic is instilled in the anterior chamber to flatten the anterior capsule by posteriorly displacing the capsular bag so as to help neutralize extraneous anterior zonular traction that could induce a peripheral extension (recall Figure 5-5). CCC enlargement after IOL implantation should generally be avoided, as the haptics can produce extraneous centrifugal forces on the capsular bag that may produce a peripheral extension when the intact CCC is incised to begin an enlargement.

A final aid in facilitating rhexis enlargement involves attention to the initial enlarging incision. If this incision is made normal (perpendicular) to the rhexis (point a in Figure 5-12-1), the likelihood of peripheral extension is increased because of the centrifugal force exerted by the anterior zonules (recall Figure 5-5-2). It would be difficult to convert the direction of this incision to the desired path circum-parallel to the existing CCC. In order to overcome these potential pitfalls, the initial enlarging incision should be made tangent to the CCC circle (point b), thereby initiating the tear in the appropriate direction and resisting peripheral extension. Furthermore, a critical element of CCC enlargement is the utilization of the more delicate shear technique (Figures 5-12-2 and 5-12-3) as opposed to inadvertent ripping maneuvers that would distort the delicate capsule support and lead to a higher incidence of peripheral extensions.

All of these principles can also be used to guide posterior capsulorrhexis, such as when the surgeon wishes to surround and strengthen a small rent in the posterior capsule. The only additional step would be to supplement the viscoelastic illustrated in Figure 5-12-4 with further viscoelastic posterior to the rent in order to tamponade vitreous (Figure 5-12-5), thereby reducing the chance of inadvertently inducing vitreous traction while performing the posterior capsulorrhexis.

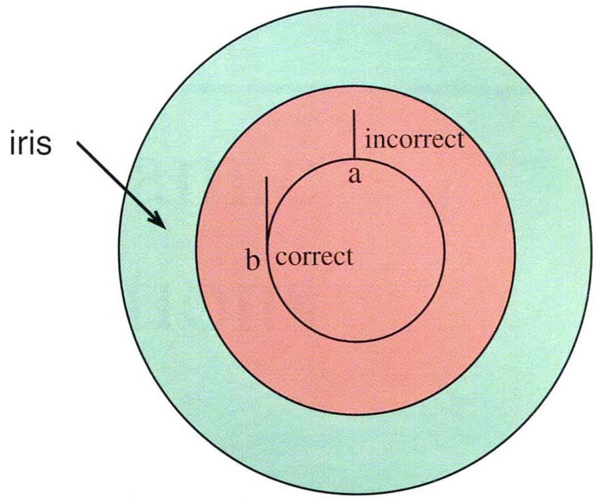


Figure 5-12-1

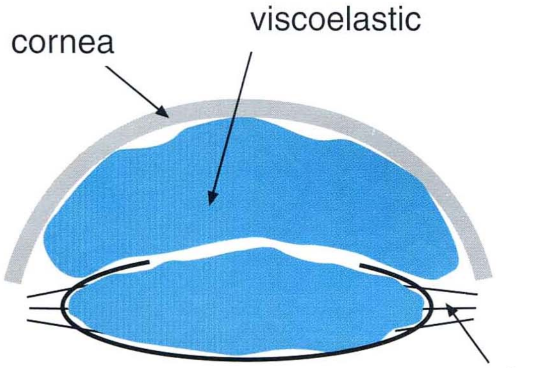


Figure 5-12-4

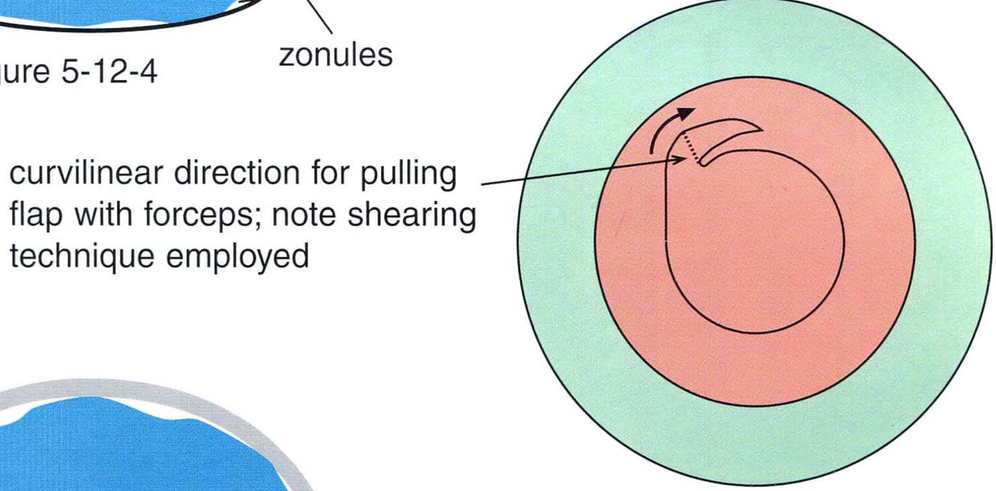


Figure 5-12-2

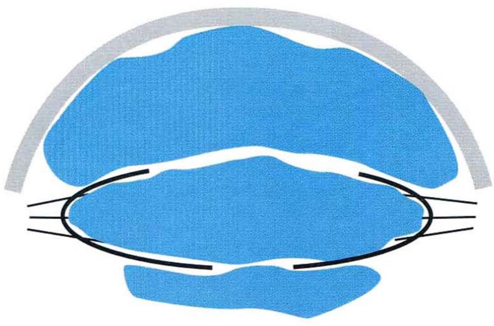


Figure 5-12-5

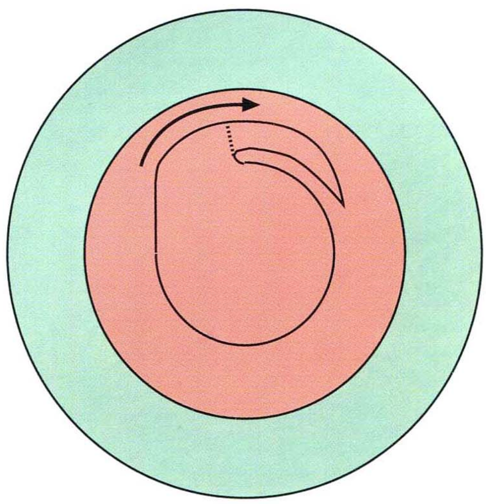


Figure 5-12-3

FIGURE 5-12

SECTION SIX

Phacodynamic Complications

Complication 1

Setup: This patient had a dense nuclear sclerotic cataract that was vertically chopped into multiple fragments, all but one of which have been effectively phacoaspirated with good followability. Parameter settings on this flow pump machine during the chopping and fragment removal phase of surgery are 35% ultrasound power (linear pulse mode at 8 pulses per second), 30 cc per minute flow rate, 260 mm Hg vacuum limit, and 110 cm bottle height. A standard 19 Ga. phaco needle is utilized along with small bore aspiration line tubing to help control surge.

Problem: Despite the good followability with all previously chopped fragments, the last fragment randomly moves around the anterior chamber. Although it has some predilection to migration toward the paracentesis incision (chopper entry) as well as the main phaco incision site, it is not drawn toward the phaco needle's aspiration port (Figure 6-1). With pedal position 2 engaged, the aspiration level tone from the phaco machine is noted to be relatively high in pitch, with occasional sounds from the occlusion indicator.

Solution: The abrupt interruption of followability is an indication of a significant loss of fluidic function. The surgeon may be tempted to pursue the fragment with the phaco needle, perhaps trying to feed it mechanically into the aspiration port with the chopper while engaging pedal position 3. This maneuver would likely cause an incisional burn due to applied ultrasound in the absence of adequate cooling flow. Insufficient flow is evident because of the high vacuum tones and occlusion indications heard in the presence of an open aspiration port that should be allowing free flow and strong currents that would ordinarily attract the fragment to the aspiration port (recall Figure 2-4). The fragment is drawn toward the incision sites because of the mild incisional leakage that creates outflow currents at these locations, which ordinarily would be more than compensated for by normal aspiration outflow through the phaco needle's aspiration port. Therefore, the surgeon must recognize this interruption in aspiration outflow and followability, and realize that half of the phaco machine's functioning has been compromised, both in terms of efficiency of phacoaspiration as well as safety for cooling of the ultrasonic needle.

The instruments are removed from the eye after viscoelastic is injected to help maintain the chamber and remaining fragment. A test chamber is placed over the phaco needle and troubleshooting reveals an accumulation of dark brown nuclear particles occluding the aspiration line, which were caused by the combination of the large bore of a standard 19 Ga. phaco needle along with the small bore aspiration line tubing. Pedal position 2 continues to produce high vacuum tones and occasional occlusion tones, and observation of the irrigating bottle's drip chamber reveals only scant activity that is inconsistent with the moderately high commanded flow rate of 30 cc/min. As pedal position 2 is maintained, the tubing is externally massaged to milk the brown fragments through. The fragments are seen to mobilize and disappear as the vacuum tone drops and the occlusion tones cease, indicating the reestablishment of flow within the fluidic circuit. The phaco needle may now be replaced in the eye for effective and safe phacoaspiration of the remaining fragment with good followability. The surgeon may wish to use a variable bore phaco needle such as the MicroFlow (Bausch & Lomb Surgical) or Flare Tip (Alcon) to produce smaller nuclear fragments with less tendency to clog in future cases.

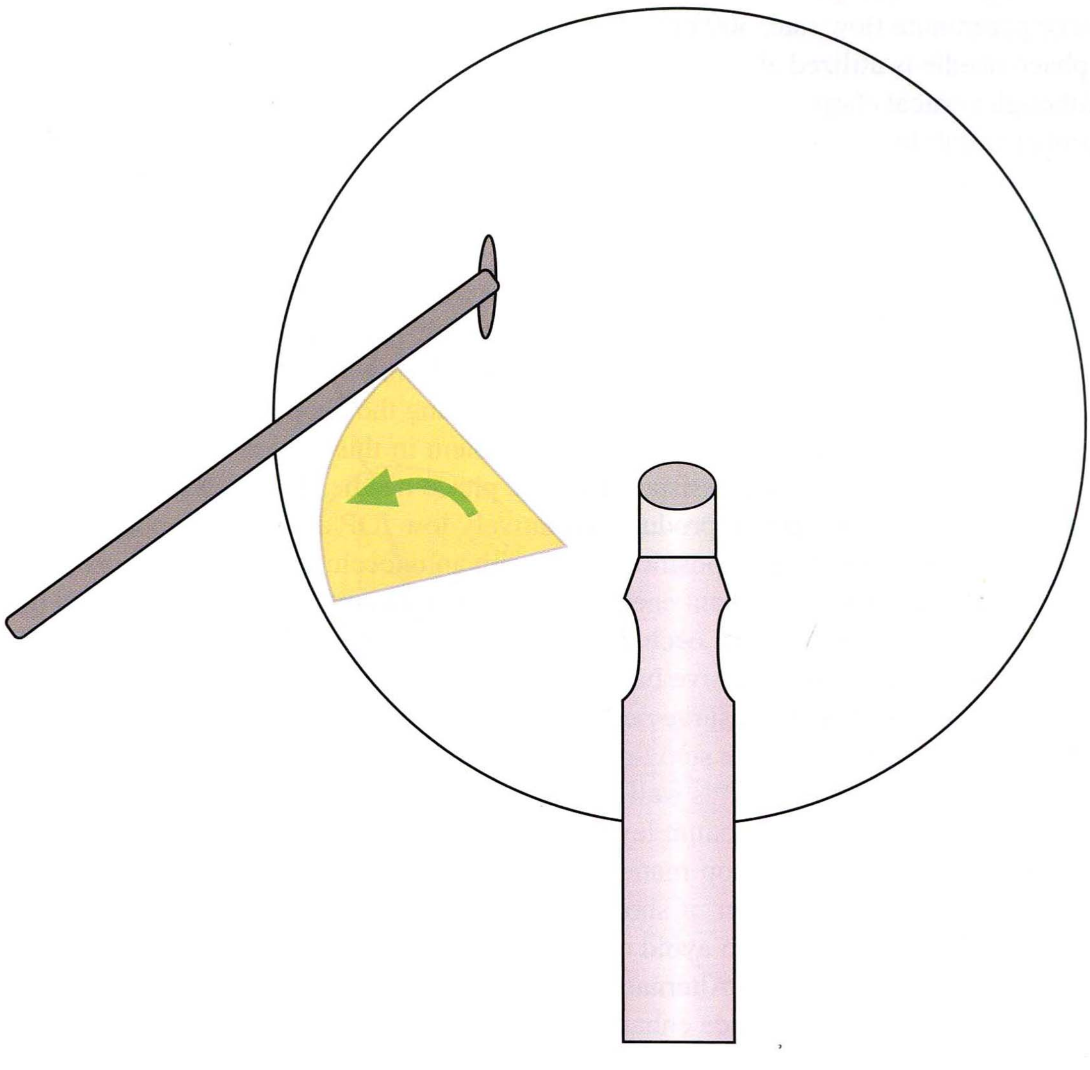


FIGURE 6-1

Complication 2

Setup: This patient had a dense nuclear sclerotic cataract that was vertically chopped into multiple fragments. Parameter settings on this flow pump machine during the chopping and fragment removal phase of surgery are 35% ultrasound power (linear pulse mode at 8 pulses per second), 40 cc per minute flow rate, 300 mm Hg vacuum limit, and 80 cm bottle height. A standard 19 Ga. phaco needle is utilized along with small bore aspiration line tubing to help control surge.

Although vertical chopping was performed without incident, the surgeon experiences anterior chamber instability upon beginning carouseling phacoaspiration of the chopped fragments. The instability is manifest as irregularly pulsatile dimpling of the cornea accompanied by constrictions of the pupil along with shallowings of the anterior chamber as appreciated through stereo microscopy.

Problem: Post-occlusion surge is occurring as the fragment is phacoaspirated in a carouseling fashion, whereby moments of complete occlusion are interspersed with partial breaks in occlusion as shown in Figure 6-2. Surge was not an issue during the vertical chopping portion of the procedure because high vacuum was applied only during the chop when complete occlusion of the aspiration port precluded any outflow. The problem in this case is one of parameter settings that are exacerbated by a low resistance 19 Ga. phaco needle. The high flow rate and relatively low bottle height combine to produce a relatively low IOP and shallow chamber even at steady state baseline when in pedal position 2 and with an unoccluded aspiration port. The high vacuum of 300 mm Hg adds compliant energy to the fluidic circuit upon occlusion (ie, when the carouseling fragment is completely occluding the aspiration port). When this surplus fluidic energy is added to the already excessive baseline outflow upon momentary fragment breakdown and opening of the aspiration port, surge occurs (see also Figure 1-48).

Solution: The most immediate step that the surgeon can take is to raise the bottle height to establish both a deeper baseline IOP as well as more infusion pressure reserve to combat momentary surges. Simultaneously, the vacuum level should be lowered because the high level needed for gripping during the vertical chop maneuvers is no longer required or appropriate for phacoaspiration of fragments. However, it should probably not be lowered excessively (ie, below 240 mm Hg in this case) in order to avoid clogging of the aspiration line with this dense nucleus, as was discussed in Figure 6-1. Alternatively or additionally, a Cruise Control can be readily added to the aspiration line to provide enhanced resistance to surge (see also Figure 1-48-4). For future cases, the surgeon will want to consider a variable lumen phaco needle such as the Flare Tip (Alcon) or MicroFlow (Bausch & Lomb Surgical) in order to have higher fluidic resistance and therefore more anterior chamber stability and more resistance to surge.

Although not an issue in this case, another potential source of anterior chamber instability could be momentary interruptions of inflow infusion pressure. A common cause of this problem is inadvertent excessive withdrawal of the phaco needle during pedal position 2 or 3, such that the irrigation ports are momentarily within the incision. Were this a problem, the surgeon's technique should first be corrected before turning to technology such as parameter adjustment discussed above.

When phacoaspirating the last few nuclear fragments or residual epinucleus, try to position the second instrument (if blunt-tipped such as the Seibel Chopper) between the posterior capsule and phaco tip. Orient the instrument so that the distal bend is parallel to the iris plane, thereby maximizing surface area in case of unexpected surge and posterior capsule contact. This maneuver will minimize the pressure at the point of potential capsule contact and therefore reduce the chances of posterior capsule rupture.

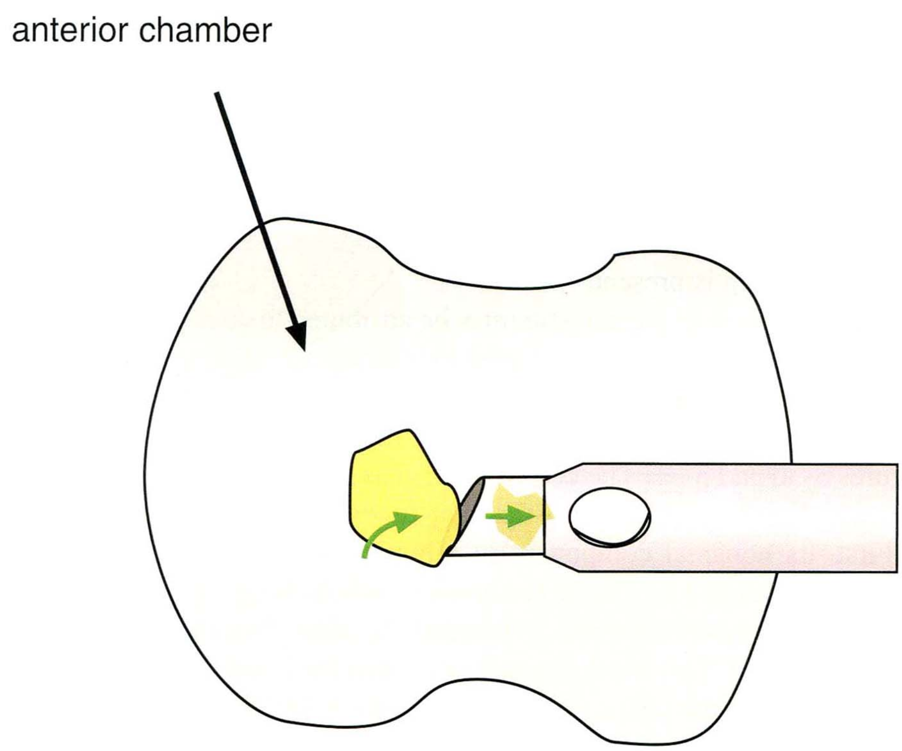


FIGURE 6-2

Complication 3

Setup: This patient had a moderately dense nuclear sclerotic cataract that has been grooved and cracked into two heminuclei in preparation for a Stop and Chop Maneuver whereby the phaco tip will impale one of the heminuclei and use vacuum to mobilize it centrally for easier placement of the chopping instrument (see also Figures 2-16-1 and 2-16-2). Parameter settings on this flow pump machine in Figure 6-3 are 35% ultrasound power (linear pulse mode at 8 pulses per second), 30 cc/min flow rate, 300 mm Hg vacuum limit, and 105 cm bottle height. A 20 Ga. micro-Kelman phaco needle is utilized for the first time by this surgeon along with small bore aspiration line tubing to help control surge.

The phaco needle was embedded into the central densest portion of the heminucleus utilizing light linear ultrasound energy to facilitate a tight vacuum seal. Ultrasound was then discontinued by raising the pedal from position 3 to position 2, and the surgeon waited a moment for vacuum to build to the preset level (as confirmed by the occlusion indicator bell) before attempting to pull the heminucleus centrally. However, rather than mobilizing the heminucleus as planned, the phaco needle simply pulled out of the heminucleus; therefore, insufficient grip is present.

Problem: Insufficient grip can sometimes be attributed to an insufficient vacuum setting at the phaco machine. However, the surgeon is using a level that has proven adequate in similar cases in the past. Other potential problems could theoretically be improper technique in securing a vacuum seal, but this surgeon has followed all of the guidelines discussed in Figures 3-30 and 3-31. The culprit in this case is the first-time use of the Kelman micro needle, which has two characteristics that fundamentally affect gripping ability in this setting. First, its nonaxial component of vibration, while excellent for sculpting, is counterproductive for producing a tight vacuum seal when chopping; note the channel created by impaling (dashed outline) that is progressively wider than the phaco needle diameter toward its distal extent. This loose channel promoted the break of the vacuum seal upon attempted manipulation of the phaco tip (see also Figure 3-31C). The second problem is the smaller aspiration port surface area of this 20 Ga needle relative to the standard MicroFlow needle that was previously utilized by this surgeon. The smaller surface area produces less grip for the same 300 mm Hg that was adequate in the past when the surgeon used a standard MicroFlow needle with a larger aspiration port surface area (Figure 1-60).

Solution: For now, the surgeon can attempt to compensate by increasing the vacuum parameter (eg, 350 to 400 mm Hg) and reengaging the heminucleus at a different location utilizing even lighter ultrasound power to help tighten the vacuum seal. Changing the flow parameter would not affect grip in this case; it would only alter the rise time. If these adjustments are still insufficient, a traditional Nagahara method may be employed with dissection of the chopper around the nondisplaced in situ heminucleus. For future chopping cases, the surgeon may wish to avoid Kelman style needles, especially in the smaller 20 Ga. size.

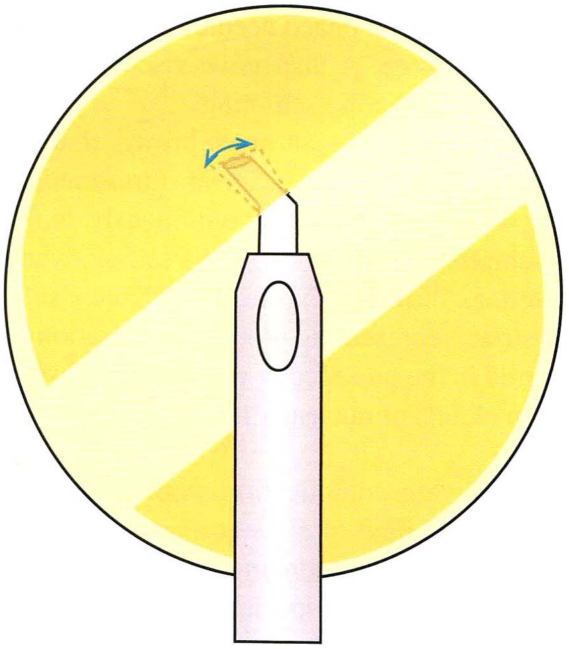


Figure 6-3-1

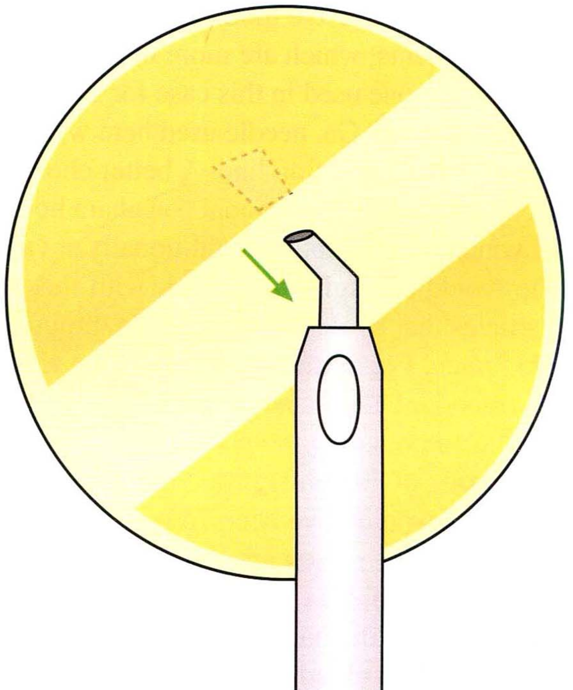


Figure 6-3-2

FIGURE 6-3

Complication 4

Setup: The surgeon is sculpting the initial groove of a Stop and Chop Method in this very dense 4+ nuclear sclerotic cataract. Parameter settings on this flow pump machine during the chopping and fragment removal phase of surgery are 50% linear ultrasound power, 30 cc/min flow rate, 30 mm Hg vacuum limit, and 80 cm bottle height. (The same situation would be represented by a vacuum pump set at 30 mm Hg commanded vacuum with the same ultrasound and bottle height settings). A standard 19 Ga. phaco needle is utilized along with small bore aspiration line tubing to help control surge. A dispersive viscoelastic had been utilized for capsulorrhexis formation just prior to beginning sculpting.

Problem: With the groove two thirds completed, the surgeon notes brown clouds of material filling the anterior chamber (Figure 6-4-1). Although using linear ultrasound, the surgeon is in fact keeping the pedal in the bottom of position 3 almost continuously, including backwards excursions of the phaco needle. Sculpting is continued in this setting, whereupon an abrupt opacification of the cornea is noted, as shown in Figure 6-4-2. Note also the incisional distortion along with radiating corneal striae, representing protein denaturation and shrinkage in this severe wound burn, which occurred in the presence of continued ultrasound in the absence of cooling fluid turnover; the brown clouds of nuclear emulsate had indicated an interruption in aspiration outflow.

Solution: Unfortunately, the solution in this severe complication would have been recognition and avoidance of several errors in judgment. First of all, any maneuver involving the non-occlusive mode of sculpting is at increased risk of producing larger, less emulsified fragments, which are more likely to clog the aspiration line, especially a small bore type such as the one used in this case for surge control. Furthermore, the relatively large lumen of the standard 19 Ga. needle used here will tend to produce relatively large fragments that also can clog the aspiration line. A better choice in this case would have been an occlusion mode technique such as traditional Nagahara horizontal chopping or else vertical chopping, neither of which uses sculpting. Additionally, a variable lumen needle such as a MicroFlow or Flare Tip would synergistically work with this occlusion mode by producing smaller emulsified particles that by definition must fit through the transition from the larger to the smaller needle lumen. Furthermore, these needles would have offered better thermal insulation relative to a standard 19 Ga. needle.

Compounding the poor choice of phaco method and needle type in this case, the vacuum setting of 30 mm Hg was simply too low for this dense nucleus. A more appropriate starting point would have been 75 mm Hg. Also, even though the ultrasound setting of 50% linear power was reasonable, its execution was inappropriate in that linear control was not utilized; the pedal was kept fully depressed most of the time, even during the backward return excursions of the handpiece during which ultrasound has no clinical function. The moment that the brown clouds were noted in the anterior chamber, the phaco needle should have been withdrawn from the eye for troubleshooting as described with Figure 6-1. The continued friction of continuous ultrasound in the absence of cooling fluid turnover around the phaco needle produced elevated temperatures at the corneal incision, resulting in this severe complication.

The use of a dispersive viscoelastic may also have contributed to the problem by limiting fluid turnover in the anterior chamber; the use of a cohesive ophthalmic viscosurgical device (OVD) or a combination technique (eg, Arshinoff Soft Shell Technique) would have allowed better anterior chamber circulation. Keeping all of the above principles in mind can help avoid incisional burns, which are often devastating to visual function and can require donor sclera or pericardium grafts even to achieve water-tight closure.

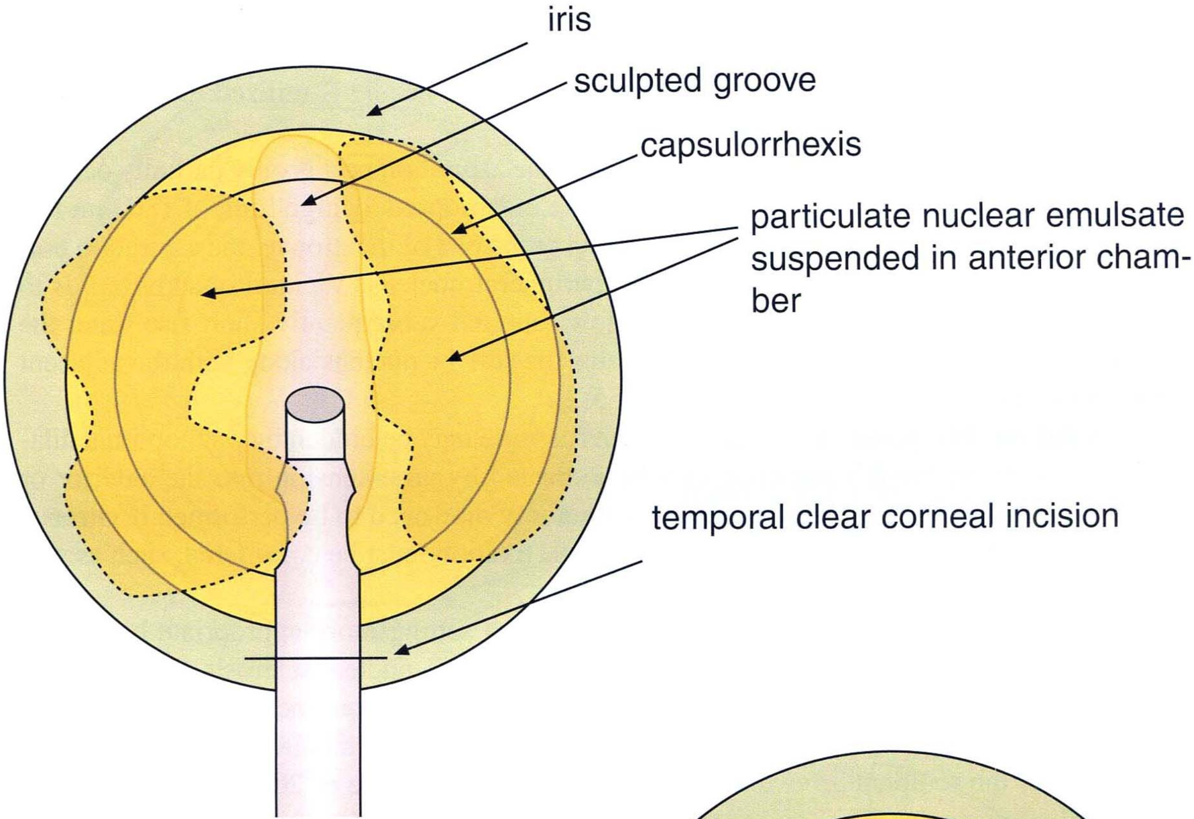


Figure 6-4-1

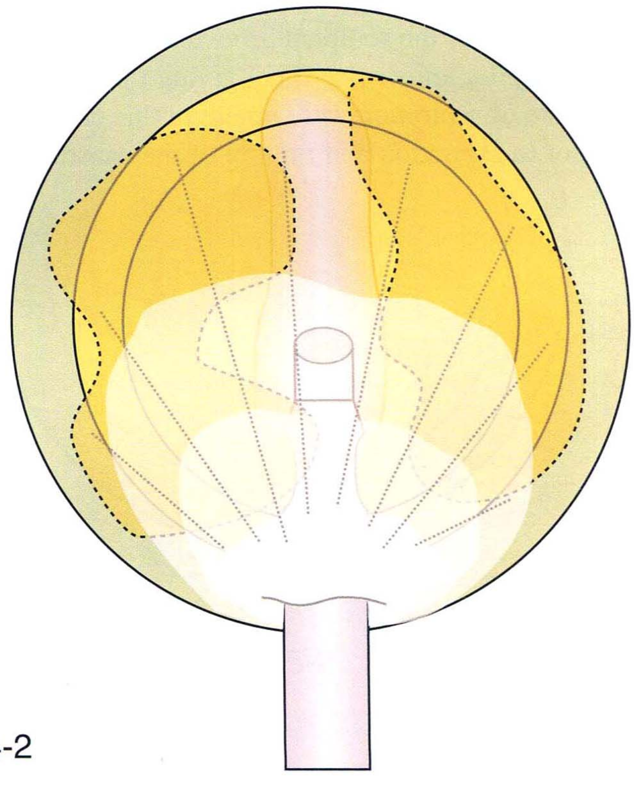


Figure 6-4-2

FIGURE 6-4

Complication 5

Setup: The surgeon is sculpting the initial groove of a Stop and Chop Method in this mostly posterior subcapsular cataract with 1+ nuclear sclerosis. Parameter settings on this flow pump machine are 50% linear ultrasound power, 30 cc/min flow rate, 180 mm Hg vacuum limit, and 90 cm bottle height. A MicroFlow phaco needle is utilized to help control surge.

Problem: During the majority of sculpting, the aspiration port is only partially occluded, and therefore vacuum does not build up to the inappropriately high limit of 180 mm Hg. However, at the distal excursion of needle travel at the end of the groove, the aspiration port does become completely occluded with the peripheral nucleus. Vacuum quickly builds to the preset limit due to the relatively high flow rate and subsequently short rise time; the resulting deformational force abruptly aspirates the soft 1+ nucleus along with the adjacent peripheral epinucleus and capsule (Figure 6-5-2).

Solution: The peripheral break in the lens capsule may be hidden by a suboptimal dilation, although the break's presence may be indicated by an extension into the anterior or posterior capsule. In this case, an anterior vitrectomy may need to be performed if vitreous is prolapsing through the break, and alternate IOL fixation must be considered, such as sulcus placement of the haptics.

The ideal solution in this case would have been setting more appropriate beginning parameters based on the preoperative assessment of soft 1+ nuclear sclerosis. A vacuum of 40 mm Hg would likely have been adequate to keep the aspiration line clear but would not have been as likely to abruptly aspirate a large amount of peripheral nucleus upon occlusion at the end of the sculpted groove. Furthermore, a lower flow rate of 20 cc/min would have produced a longer rise time, giving the surgeon more time to react if an unwanted amount or rate of aspiration were noted; in this case, the surgeon could raise the pedal to position 1 prior to aspiration and rupture of the capsule.

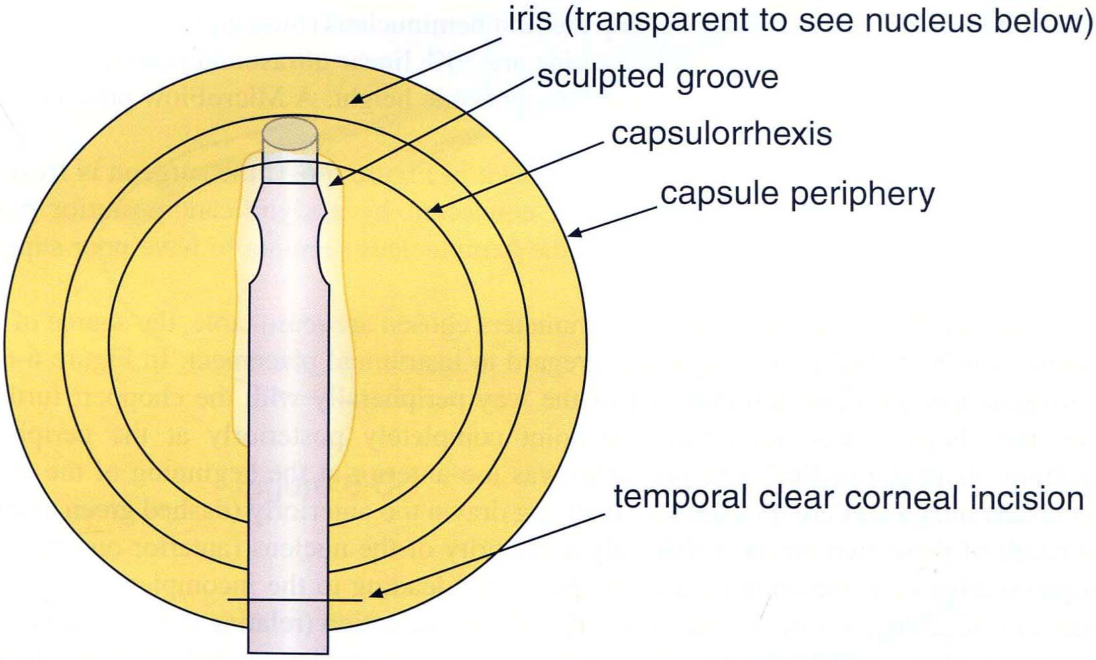


Figure 6-5-1

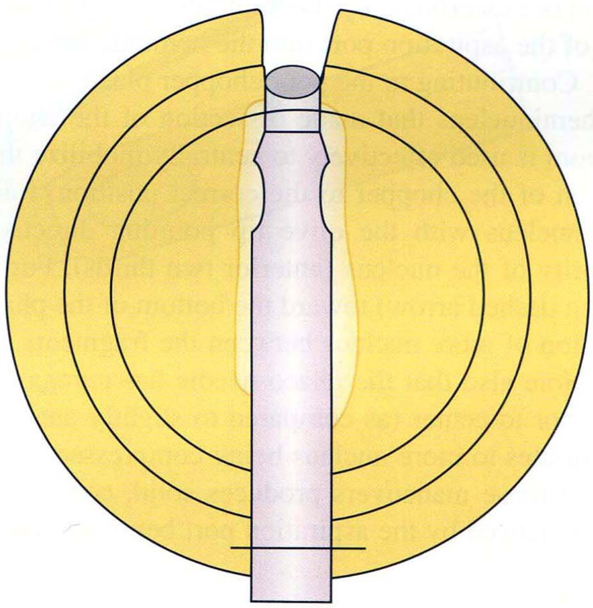


Figure 6-5-2

FIGURE 6-5

Complication 6

Setup: After having grooved and bisected the nucleus of this 3+ nuclear sclerotic cataract, the surgeon is attempting to chop the first heminucleus (Stop and Chop Maneuver). Parameter settings on this flow pump machine are 30% linear ultrasound power, 30 cc/min flow rate, 260 mm Hg vacuum limit, and 110 cm bottle height. A MicroFlow phaco needle is utilized to help control surge.

Problem: Utilizing the instruments as shown in Figure 6-6-1, the surgeon is frustrated that most of the chops are incomplete, connected by a significant posterior plate. Furthermore, the chops are awkward, with the heminucleus seeming to have poor support and grip.

Solution: While the hardware and parameters chosen are reasonable, the source of the problems can be traced to technique with regard to instrument placement. In Figure 6-6-1, the surgeon has not dissected quite all of the way peripherally with the chopper; furthermore, the chopper was not rotated to point completely posteriorly at the periphery. Therefore, its posterior limit (the olive tip) was too anterior at the beginning of the chop. This disadvantage was compounded by its being drawn too anteriorly (dashed green arrow). The result of these two errors is that only a minority of the nucleus (anterior one third) is compressed between the chopper and the phaco tip, leading to the incomplete chops with posterior bridges remaining. Furthermore, the off-axis direction (relative to the center of the aspiration port) contributes to the instability of the grip by creating a slight torque. The situation is exacerbated by the relatively poor vacuum seal caused by the insufficient penetration of the aspiration port into the heminuclear face (see also Figures 3-31 A-1 and A-2).

Contributing to the poor chopper placement in Figure 6-6-1 was the in situ position of the heminucleus that made dissection of the chopper relatively difficult. In Figure 6-6-2, vacuum is used effectively to centrally mobilize the heminucleus to facilitate an easier dissection of the chopper to the correct position, fully engaging the peripheral extent of the heminucleus with the olive tip pointing directly posteriorly, therefore encompassing a majority of the nucleus (anterior two thirds). Furthermore, it is drawn slightly posteriorly (green dashed arrow) toward the bottom of the phaco needle, resulting in even greater compression of more nucleus between the fragments and less induced torque than in Figure 6-6-1. Note also that the phaco needle has reengaged the heminucleus in a position slightly posterior to center (as compared to slightly anterior to center in Figure 6-6-1), which also contributes to more nucleus being compressed between the two instruments. The combination of these maneuvers produces solid, complete chops virtually every time. Stability is also enhanced by the aspiration port being embedded more deeply in Figure 6-6-2.

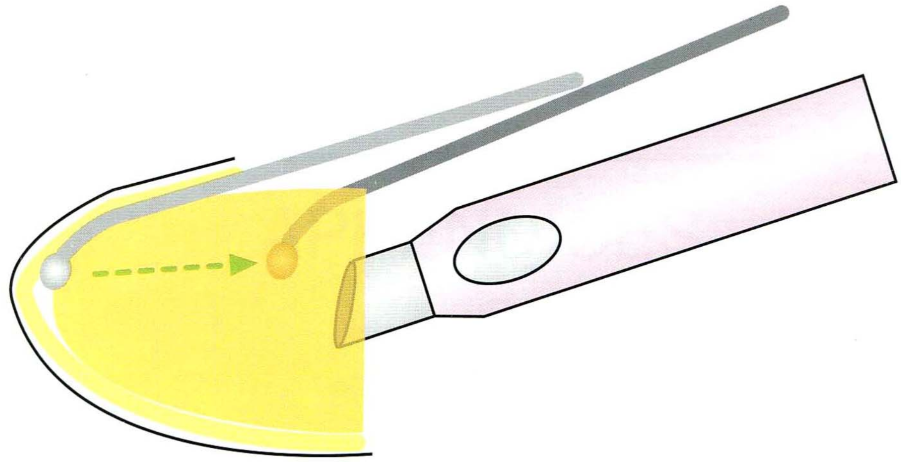


Figure 6-6-1

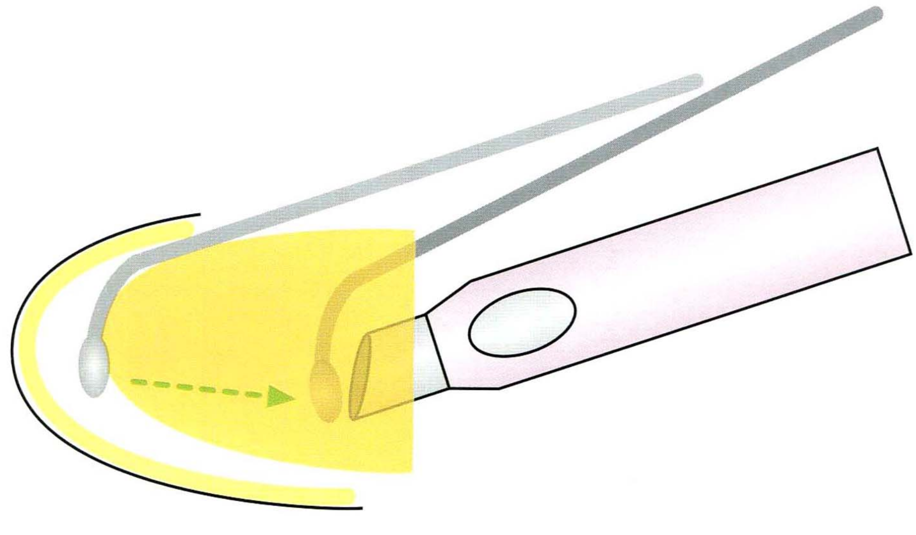


Figure 6-6-2

FIGURE 6-6

APPENDICES

Appendix A: Implied Surface Area in Units of mm Hg

The force required to suspend a column of mercury (Hg) of height (h), where volume of a cylinder = $\Pi r^2 h$ and density = ρ, is:

$$F = \text{mass} \cdot \text{acceleration}$$

$$F = (\text{density} \cdot \text{volume}) \cdot g, \text{ where } g = \text{gravitational acceleration}$$

$$F = \rho \cdot \Pi r^2 h \cdot g$$

$$\text{Pressure} = \frac{\text{force}}{\text{area}}, \text{ and area} = \Pi r^2$$

$$P = \frac{\rho \Pi r^2 h g}{\Pi r^2} = \rho h g$$

So, P is a linear function of the column height (ie, mm of Hg). Also, note in the last line of the derivation that the units of surface area (Πr^2) in the numerator and denominator cancel each other out such that the final unit of mm Hg has the surface area implied but not expressed. Therefore, when calculating the force for a given pressure and surface area, it is more convenient to convert mm Hg to PSI (pounds per square inch), as seen in Appendix B.

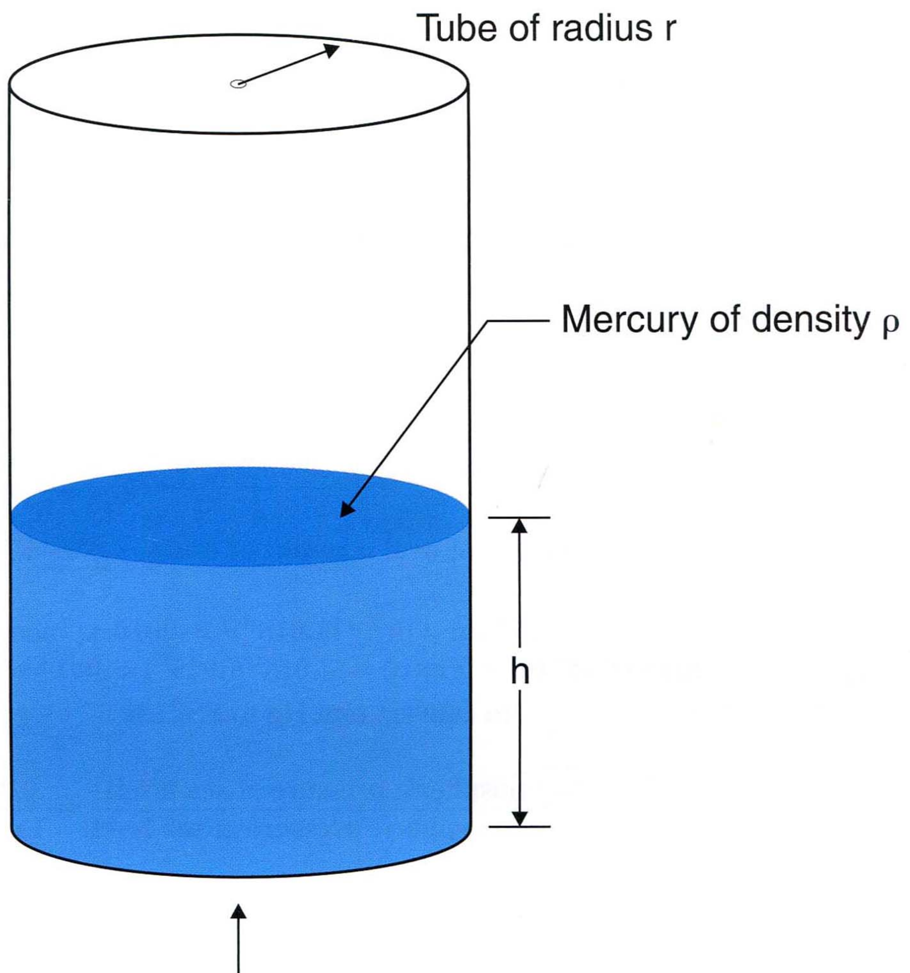


Figure A-1

Appendix B: Aspiration Port Surface Area Derivation

The formula for the surface area of a circle is $\Pi r^2 = \Pi rr$, where r = radius of the needle's distal internal diameter (ID). The formula for the surface area of an oval is $\Pi r(r_l)$, where r is the short radius of the oval (same value as the radius of a circular cross-section of the needle) and r_l is the long radius of the oval. Since r_l is always greater than r, $r(r_l)$ will always be greater than r(r), and it follows that the oval cross-section of a beveled needle's aspiration port will have larger surface area than the circular cross-section of a 0° tip's aspiration port (see Figure 1-60). A standard phaco needle's aspiration port has an ID of 0.9 mm = .035 inches. To compute r_l, the total length of the oval (diameter) is computed with trigonometric function as shown, such that:

$$\cos 45^\circ = \frac{b}{c}\text{, where } \cos 45^\circ = .707 \text{ and } b = .035''$$

$$.707 = \frac{.035''}{c}$$

$$c = \frac{.035''}{.707} = .050'' = \text{long diameter of oval}$$

$$r_l = \text{long radius of oval} = \frac{\text{long diameter of oval}}{2} = \frac{.050''}{2} = .025''$$

$$r = \text{short radius of oval} = \text{radius of } 0^\circ \text{ tip} = \frac{.035''}{2} = .018''$$

$$\text{area of } 0^\circ \text{ tip} = \Pi r^2 = \Pi(.018'')^2 = .0010 \text{ sq inch}$$

$$\text{area of } 45^\circ \text{ tip} = \Pi(r)(r_l) = \Pi(.018'')(.025'') = .0014 \text{ sq inch}$$

to convert mm Hg to PSI use

$$\frac{14.7 \text{ PSI (atmospheric pressure at sea level)}}{760 \text{ mm Hg (atmospheric pressure at sea level)}} = \frac{.019 \text{ PSI}}{1 \text{ mm Hg}}$$

$$\text{so, for pump vacuum of 100 mm Hg} = 100 \text{ mm Hg} \bullet \frac{.019 \text{ PSI}}{\text{mm Hg}} = 1.9 \text{ PSI}$$

$$\text{holding force of vacuum for } 0^\circ \text{ tip} = \frac{1.9 \text{ lbs.}}{\text{sq inch}} \bullet .0010 \text{ sq inch} = .0019 \text{ lbs}$$

$$\text{holding force of vacuum for } 45^\circ \text{ tip} = \frac{1.9 \text{ lbs.}}{\text{sq inch}} \bullet .0014 \text{ sq inch} = .0027 \text{ lbs}$$

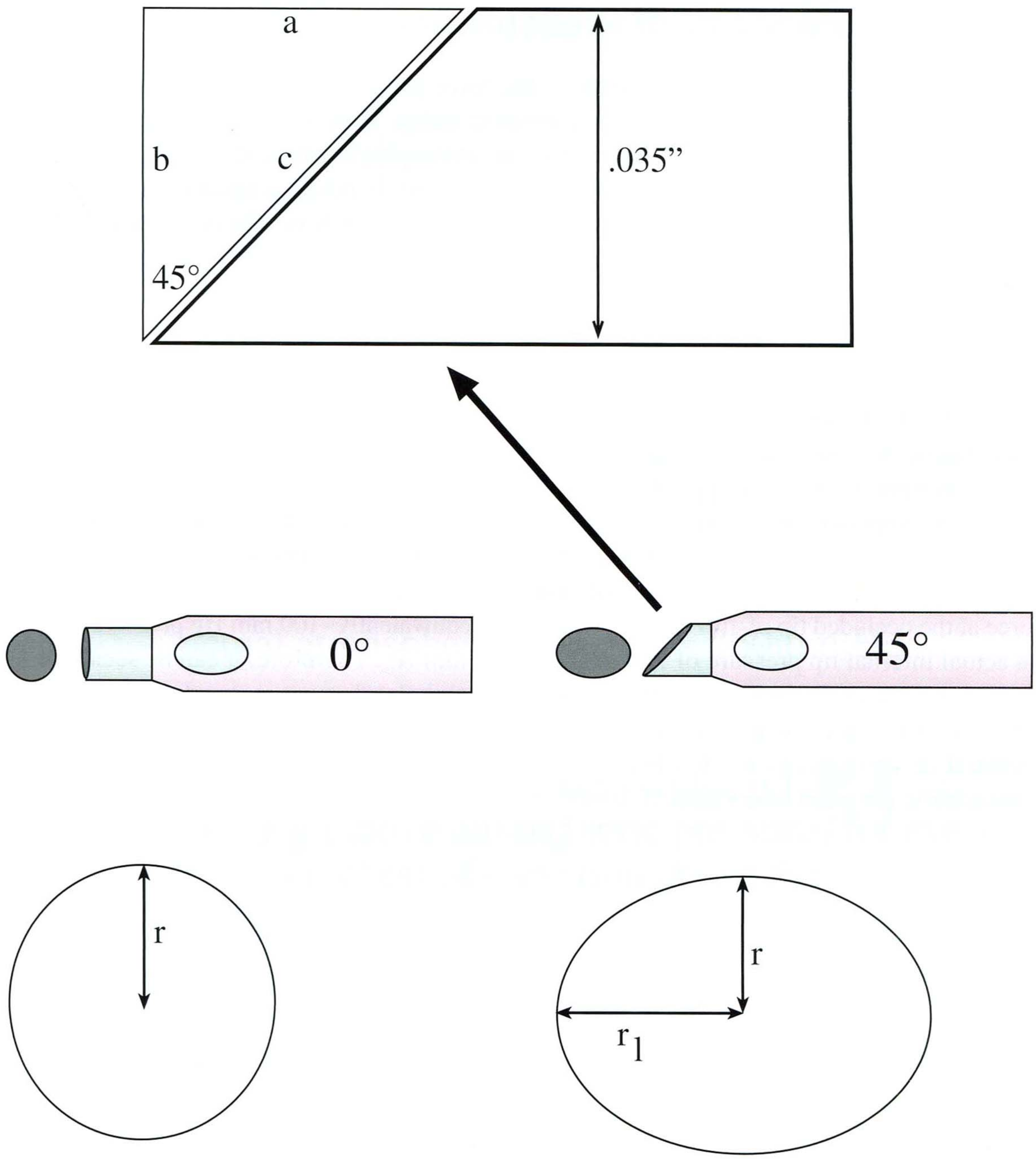


Figure B-1

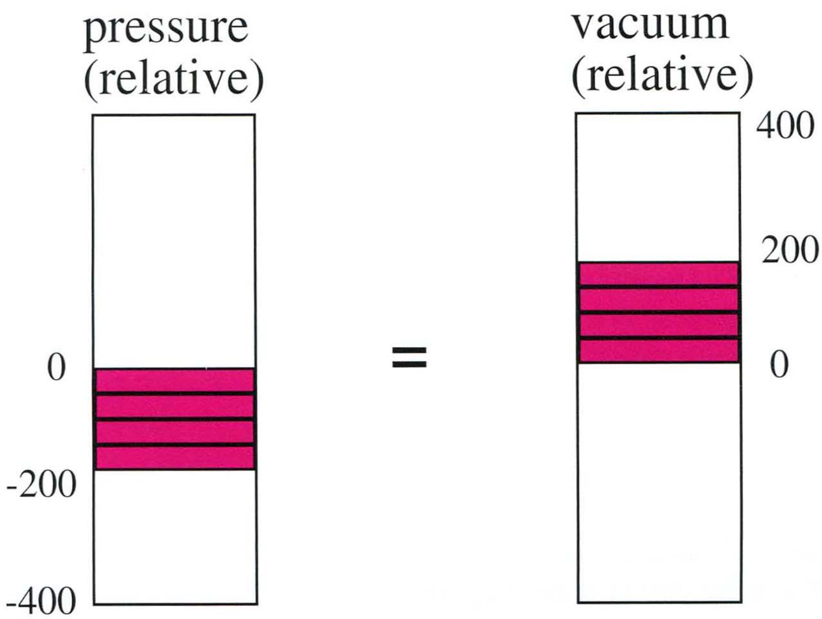
Appendix C:
Summary of Pressure Terminology

As defined in Appendix A, pressure is the force per unit area. Any pressure above the absolute vacuum of outer space is a positive value. However, pressures are often expressed as a pressure differential relative to atmospheric pressure at sea level, in which case pressures above atmospheric are expressed as positive numbers and pressures less than atmospheric are expressed as negative numbers. Pressures less than atmospheric are also often expressed as units of (relative) vacuum, which are by convention positive numbers. For example:

200 mm Hg vacuum = -200 mm Hg pressure

Both of the above values refer to a pressure that is 200 mm Hg below ambient atmospheric pressure (see accompanying figure).

Atmospheric pressure is defined as 760 mm Hg or 14.7 PSI at sea level. If a Goldmann Applanation Tonometer produces a reading of 20 mm Hg, this then represents the positive pressure above atmospheric pressure, such that the eye's actual hydrostatic pressure is 760 + 20 = 780 mm Hg. Similarly, a phaco pump which produces a holding force at the occluded tip of 100 mm Hg vacuum (or equivalently -100 mm Hg pressure) has an actual internal tip pressure of 760 to 100 = 660 mm Hg. Therefore, it can be seen that the numbers used in phaco surgery, as well as ophthalmology in general, represent a pressure differential as opposed to an actual pressure. Moreover, a relative pressure differential or vacuum can exist between two pressures even if neither pressure is below atmospheric pressure (see Figure 1-10-1).



Zero (on meter) = atmospheric pressure
actual atmospheric pressure = 760mm Hg

Note: The irrigating bottle yields an IOP of 11mm Hg (above atmospheric pressure) for every 15cm (6 inches) of elevation above the eye. This relationship is accurate for hydrostatic pressures in pedal position 1; the IOP decreases in pedal positions 2 and 3 in proportion to the pump strength and to the degree of aspiration port occlusion (see Figures 1-11 and 1-41).

Figure C-1

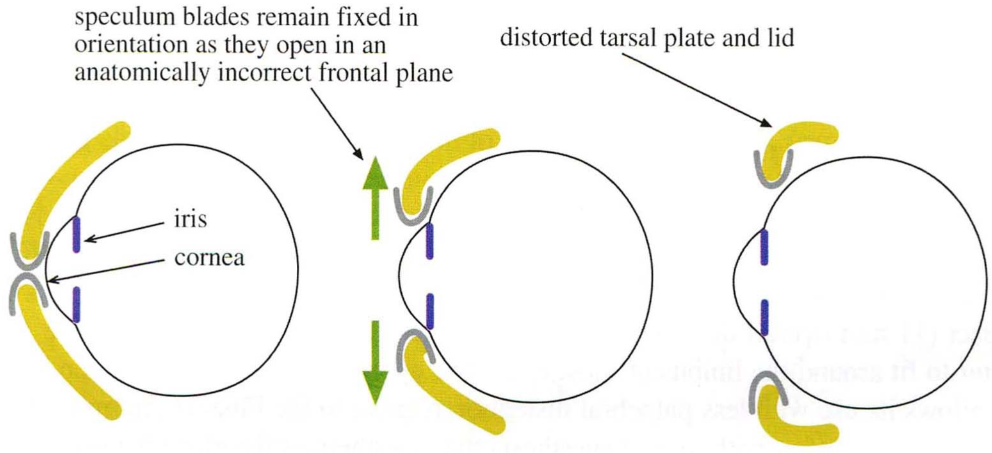
Appendix D
Phacodynamic Analysis in Instrument Design

As seen throughout this textbook, Phacodynamics parses surgical procedures into their component parts with regard to the fundamental science underlying the instrumentation and microsurgical maneuvers. This same logic applies to instrument design as well, as described for the Seibel Choppers (see Figure 3-28). Depending on the surgical challenge, instrument design may take on the process of simple refinement vs a completely different design approach, as opposed to trying to fix a fundamentally faulty design. This latter approach was taken with the Seibel 3-D Lid Speculum (Bausch & Lomb Surgical, Rhein Medical).

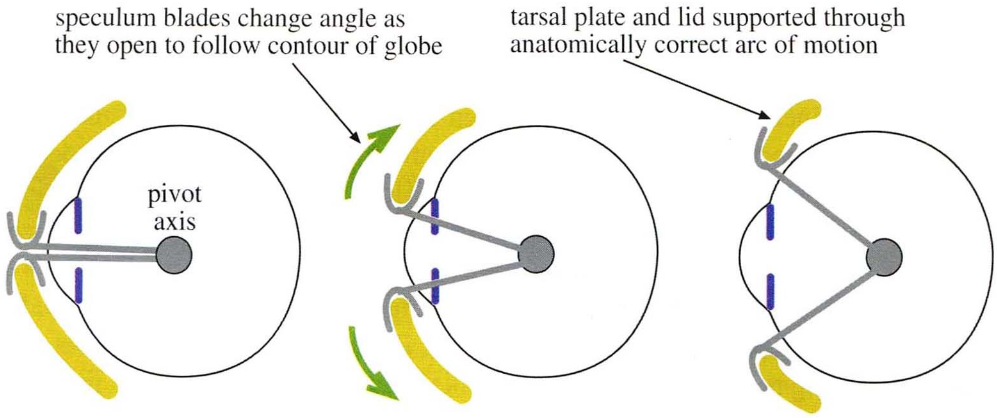
Seibel 3-D Lid Speculum

As described above, a reverse engineering approach was required for this instrument based on a fundamental flaw in the design of existing lid speculums. The problem became evident with the increasing use of topical anesthesia, which affects the globe but not the surrounding adnexa. Patients often experienced discomfort with speculum engagement and expansion, and closer inspection revealed that essentially all existing traditional lid speculums had a functional pivot axis oriented in an anterior-posterior direction (either an actual pivot joint or simply a connection point for a wire spring). As the speculum blades opened around this axis, they maintained their orientation in a frontal plane, resulting in distortion of the lids and tarsal plate (see top portion of Figure D-1).

In order to solve this problem, reverse engineering began with the goal of having the speculum blades change their angle as they opened in order to follow the contour of the globe and therefore gently support the lids in an anatomically correct arc of motion. With this motion defined, linkage arms were added that needed to connect to a linkage point, and in order to maintain the defined motion, this linkage point had to be a pivot axis oriented laterally, essentially parallel to a line drawn between the medial and lateral canthi. Note that this pivot axis orientation is fundamentally different from the anterior-posterior orientation of traditional speculums, a design that did not lend itself to evolutionary modification but rather required a complete redesign (see lower portion of Figure D-1). Therefore, the starting point for the new design was the eyelid anatomy and function rather than existing instrumentation.



Traditional Lid Speculum (Side View)



Seibel 3-D Lid Speculum (Side View)

Figure D-1

Seibel-Fine Fixation Ring

Dr. Howard Fine modified the original Thornton globe fixation ring by adding a ring gap in order to allow access for a clear corneal phaco incision while still fixating the globe. The Fine-Thornton ring played an important role in facilitating surgeons' transitions to the new clear corneal methods; however, although the basic design of the instrument was sound, a Phacodynamic analysis of its design and function revealed several areas for refinement. The essential function of the instrument was to provide globe fixation in four quadrants around the limbus, a goal that was not compromised by having the ring gap in between two of the quadrants. This goal could still be achieved by altering the center of the ring upwards and inwards as shown in the diagrams of the Seibel-Fine Fixation Ring (Bausch & Lomb Surgical, ASICO). While still providing fixation in four quadrants (1, 2, 3, 4 in upper right diagram of Figure D-2), this design is much more compact (11 mm overall diameter vs 15 mm diameter) while providing the same 13 mm effective ring diameter to fit around the limbus of most eyes. The approximately 30% reduction in size of the new instrument allows its use with less palpebral distention relative to the Fine-Thornton ring, therefore facilitating better patient comfort with topical anesthesia that anesthetizes the globe but not the lids. Similarly, for a given palpebral fissure, the globe may be manipulated more with the compact instrument, allowing more flexibility in surgical approach and in optimizing the red reflex.

In addition to indenting the ring from the top view as described above, the same area of the ring was raised anteriorly away from the limbus as well. This design change did not adversely impact the effectiveness of four quadrant fixation (1, 2, 3, 4 in upper right diagram of Figure D-2). However, it offered the advantage of additional surgical approaches for the paracentesis incision through these raised segments without having to reorient the main ring gap.

Another area for refinement in the original design involved the placement of the pivot axis (dashed double arrow), which had been retained through the geometric center diameter (red dot) of the fixation ring, just as with the Thornton design that had no ring gap. However, the lower mass on the side of the ring with the gap caused the opposite side to be imbalanced and hang downward if the pivot axis was mobile (lower left diagram); the alternative was to have a stiffer pivot axis that required two hands to position the instrument. This problem was overcome by simply mounting the mobile pivot axis (dashed double arrow) at the ring's center of gravity (blue dot) in the Seibel-Fine Fixation Ring, which enables easy one-handed positioning because the ring remains balanced and parallel with the floor and limbus regardless of the handle inclination.

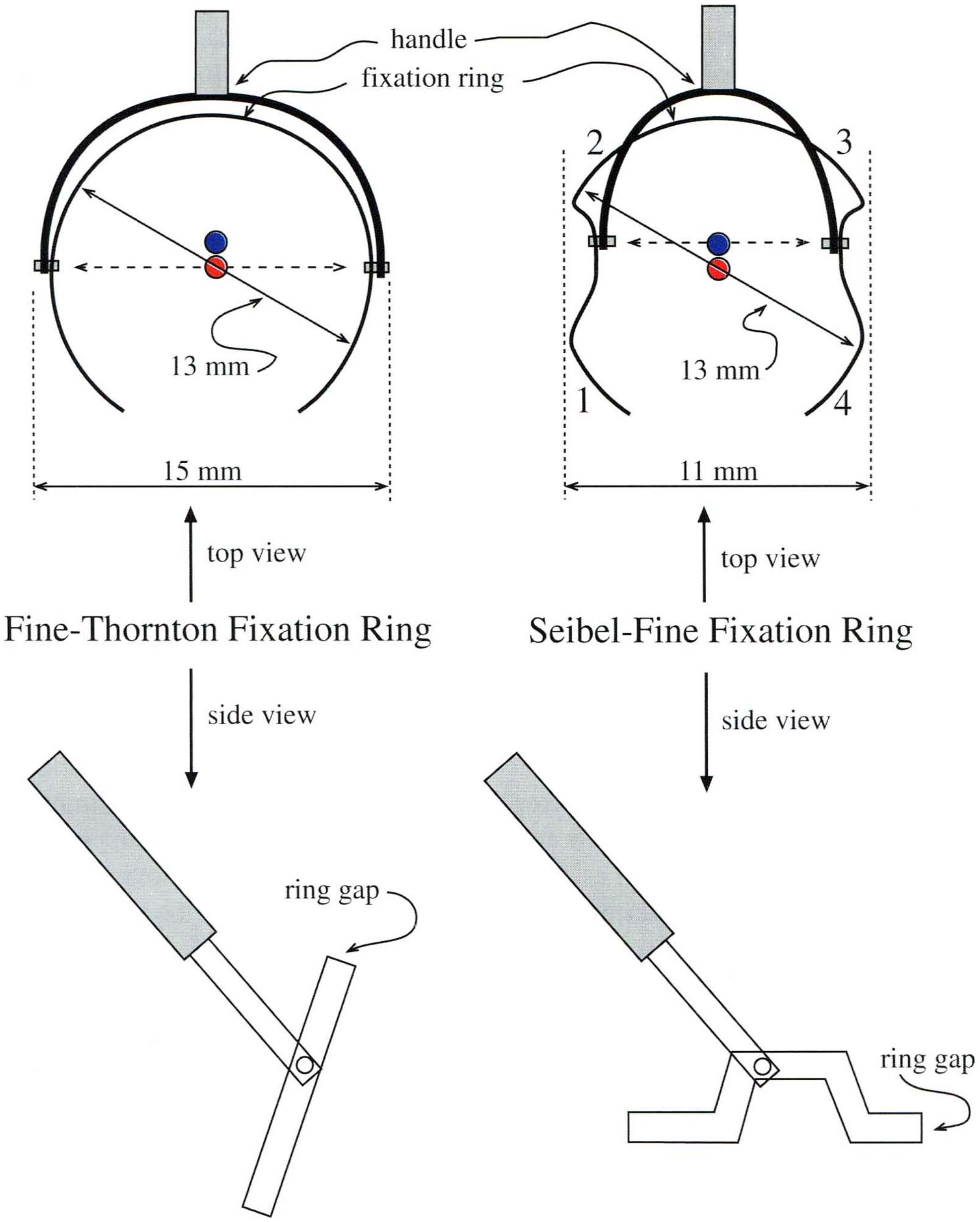
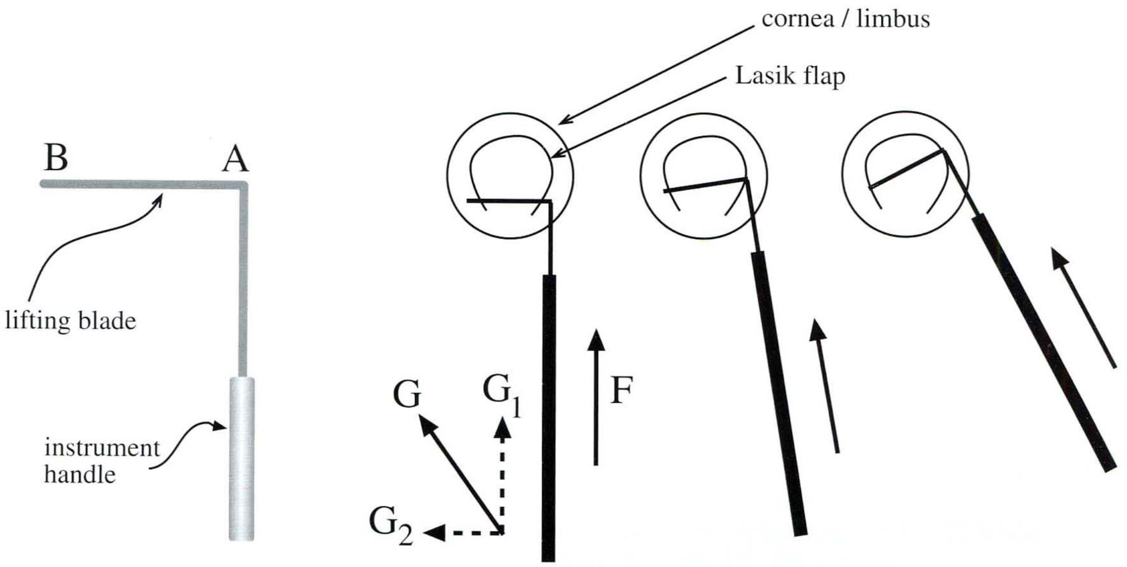

handle
fixation ring
2
3
13 mm
13 mm
1
4
15 mm
11 mm
top view
top view
Fine-Thornton Fixation Ring
Seibel-Fine Fixation Ring
side view
side view
ring gap
ring gap

Figure D-2

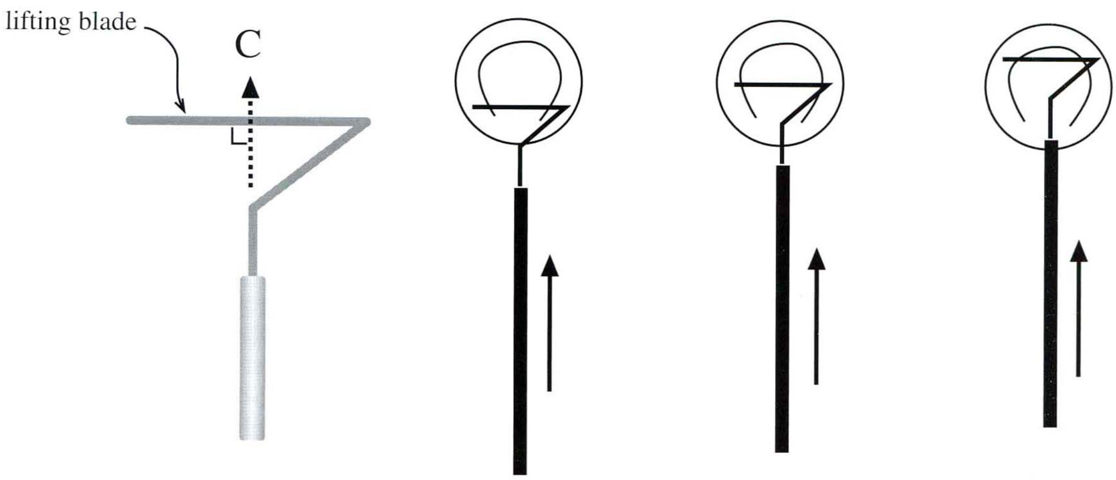
Seibel IntraLASIK Flap Lifter and LASIK Enhancement Instrument

When lifting a LASIK flap for enhancement or when lifting some primary IntraLASIK flaps, variably moderate amounts of resistance are encountered when sliding the lifting blade of an instrument through the interface between the flap and the stromal bed. Traditional flap lifting instruments have the basic structure shown in the upper diagrams with the main handle shaft attaching to the lifting blade at a right angle (90°) at point "A". A typical surgical situation is to insert the instrument in the flap interface at the hinge point and to then push away from the hinge to fully dissect the interface. When a surgeon applies force "F" along the handle shaft in the desired direction of dissection, flap interface resistance causes a drag at point "B", resulting in an induced torque as shown in the upper diagram of Figure D-3. Even though the resistance force is identical at point B and point A, point B has a greater torque effect because the force is applied at a greater distance away from the effective pivot axis at point A (see Figure 3-12). The surgeon must fight this induced torque while simultaneously trying to move the lifting blade through the interface. In order to dissect the flap in direction F, the surgeon would have to awkwardly use force "G", which has a component force vector G1 that drives the instrument forward while component vector G2 combats the induced torque from the flap interface.

Like traditional lid speculums that have an anatomically incorrect pivot axis of opening (Figure D-1), traditional LASIK flap lifters have a fundamentally awkward design by virtue of their 90° connection between the lifting blade and the handle shaft as described above. In order to more effectively apply force when using the instrument, a fundamental redesign was required. As with the Seibel 3-D Lid Speculum, a reverse engineering approach was adopted whereby the goal was to apply a linear, torque-free force to the lifting blade. With this goal in mind, the unique design of the Seibel IntraLASIK Flap Lifter (Rhein Medical) in the lower diagram of Figure D-3 aligns the instrument handle so that it is perpendicular to and centered on the lifting blade. Therefore, a force vector that is aligned along the handle is transmitted to the center of the lifting blade (see short dashed arrow at point "C") so that no torque is induced when lifting a flap. The surgeon therefore has better control as all attention may be directed to moving forward through the flap interface without having to simultaneously fight induced torque as with the traditional flap lifting instruments.



Traditional Flap Lifting Instrumentation



Seibel IntraLasik Flap Lifter and Enhancement Spatula

Figure D-3

Bibliography

Akahoshi T. *Double chopper prechop*. Presented at the 1996 ASCRS Film Festival. First Place, New Techniques.

Allergan Medical Optics Department of Professional Education. One-Handed Method. *Small Incision Surgery with Richard Livernois, MD*. Irvine, Calif. Call for video 800-347-4500.

Arshinoff S. *Dispersive/cohesive viscoelastic soft shell technique*. Presented at the 1996 ASCRS Film Festival. First Place, Surgical Maneuvers.

Barrett G. *Maxi-flow phaco needle*. Presented at the 1995 ASCRS Film Festival. First Place, Cataract/Implant Surgery.

Blumenthal M, Assia EI, Chen V, Avni I. Using an anterior chamber maintainer to control intraocular pressure during phacoemulsification. *J Cataract Refract Surg*. 1994;20:93-96.

Brown, DC, Advanced surgical technique: The phaco flip revisited. *Video Journal of Ophthalmology*. 1999:XV(3).

Colvard DM, Kratz RP. Cataract surgery using the Erbium laser. In: Fine IH. *Phacoemulsification: New Technology and Clinical Application*. Thorofare, NJ: SLACK Incorporated; 1996.

Dodick JM. Laser phacolysis of the human cataractous lens. *Dev Ophthalmol*. 1991;22:58-64.

Dodick JM. Current techniques in laser cataract surgery. In: Fine IH. *Phacoemulsification: New Technology and Clinical Application*. Thorofare, NJ: SLACK Incorporated; 1996.

Eichenbaum, DM. Paradigm system: A laser probe for cataract removal. In: Fine IH. *Phacoemulsification: New Technology and Clinical Application*. Thorofare, NJ: SLACK Incorporated; 1996.

Fine IH. Chip and flip. *Video Journal of Ophthalmology*. 1991;VII(4).

Fine IH. Choo choo chop and flip for difficult cases. *Video Journal of Ophthalmology*. 2000:XVI(1).

Fishkind WJ. *Revelation: The origin of emulsification*. Presented at the 2001 ASCRS Film Festival. First Place, Quality Teaching.

Fukasaku H. *Snap and split phaco technique*. Presented at the 1995 ASCRS Film Festival. Runner Up, New Techniques.

Gimbel HV. Divide and conquer. Phacoemulsification. ISBN 1-56283-004-X. *Video Journal of Ophthalmology*. 800-822-3100.

Koch P. Stop and chop. In: *Mastering Phacoemulsification*. Thorofare, NJ: SLACK Incorporated; 1993.

Lindstrom RL. Surgical development: The tilt-and-tumble technique for phacoemulsification. *Video Journal of Ophthalmology*. 1999;XV(3).

Maloney WF. Kratz/Maloney two-handed method. *Video Journal of Ophthalmology*. 1987;III(4).

Nagahara K. Phaco chop. *Video Journal of Ophthalmology*. 1993;IX(3).

Nishi O, Nishi K. Preventing posterior capsule opacification by creating a discontinuous sharp bend in the capsule. *J Cataract Refract Surg*. 1999;25:521-526.

Osher RH. *The mature cataract and its sharp edges: Fact or fiction?* Presented at the 1997 ASCRS Film Festival. Grand Prize Winner.

Packer M, Fine IH, Hoffman RS. Erbium YAG laser phacoemulsification. In: Buratto L, Werner L, Zanini M, Apple D. *Phacoemulsification: Principles and Techniques*. 2nd ed. Thorofare, NJ: SLACK Incorporated; 2003.

Pfeifer V. *Phaco crack*. Presented at the 1996 ASCRS Film Festival. First Place, Cataract/Implant Surgery.

Schafer ME. Maximizing cavitation, table in optimizing phaco machine settings. *Review of Ophthalmology*, April 15 2003.

Shepherd JR. Four quadrant method. *Video Journal of Ophthalmology*. 1990;VI(2).

Werner L, Apple DJ, Pandey SK. Postoperative proliferation of anterior and equatorial lens epithelial cells. In: Buratto L, Werner L, Zanini M, Apple D. *Phacoemulsification: Principles and Techniques*. 2nd ed. Thorofare, NJ: SLACK Incorporated; 2003.

Index

FOURTH EDITION

PHACODYNAMICS

Mastering the Tools and Techniques of Phacoemulsification Surgery

Phacodynamics: Mastering the Tools and Techniques of Phacoemulsification Surgery has helped thousands of surgeons understand and benefit from the advantages of phaco technology. The revised, expanded, and updated Fourth Edition of this classic text includes over 300 simple, yet elegant, figures and illustrations detailing the latest machine technologies and surgical techniques.

In addition to examining the intricate relationship between the surgeon and the phaco machine, Dr. Barry Seibel profiles how the most recent advancements in machine technology can enhance your surgical procedures and optimize your results. With schematic figures and illustrations to accompany the detailed descriptions, surgeons can readily identify and distinguish between various flow pumps, vacuum pumps, and ultrasound power modulations. Surgery can then be customized moment by moment for each individual patient to maximize safety and efficacy.

New topics included that are unique to this Fourth Edition:

- Bimanual Microincision Phaco
- Ultrasound Power Modulations including Burst and Pulse Modes
- AquaLase and Laser Surgical Technologies
- Expanded Horizontal Chopping Techniques including PreChop
- Vertical Chopping Techniques and Instrumentation
- Bimanual Irrigation and Aspiration
- Phacodynamic Complications
- Phacodynamics of Surgical Instrument Design

Phacodynamics, Fourth Edition utilizes a simplified approach to explain all the latest advancements in phaco technology and surgery and should be in the hands of all surgeons practicing in this specialized area.

Reviews of previous editions:

"I learned more about phacoemulsification surgery (in this book) than in all previous course time. The text is brilliantly illustrated. The diagrams amplify and refine the written paragraphs. This is a book that every cataract surgeon must review. This book has my highest recommenda-tion. I wish I had written it."

- Frederick S. Brightbill, *MD, Archives of Ophthalmology*

"The other books tell you what to do. This book tells you why and how. The illustrations are superb, demonstrating clearly how phacoemulsification works and why some maneuvers must, necessarily, work better than others. This book is critical if you want to master the art and science of phacoemulsification."

-Paul S. Koch, MD, *Koch Eye Associates, Warwick, RI*

"This book will be utilized best by that cataract surgeon who wants to truly understand the technology that he holds in his hands. I am sure that this added level of comprehension would easily enhance any cataract surgeon's capabilities."

-Leonid Skorin, Jr., MD, DO, FAOCO,
Journal of the Osteopathic College of Ophthalmology and Otorhinolaryngology

ISBN 1-55642-688-7
90000
9 781556 426889

SLACK INCORPORATED
slackbooks.com