2. How to Set the Dials

TERENCE M. DEVINE, M.D.

INTRODUCTION

Several years ago I was invited by Anton Banko to speak in an upcoming meeting. After he described the proposed topic, I agreed, and he then went on to ask what title I wanted for the lecture. I turned the question back to him and he suggested "Transocular Flow and Dynamic Equilibrium in a Stable Surgical Environment," but continued by saying I should put it in my own words. I gave it considerable thought and came up with "How to Set the Dials." The point is that engineers and surgeons do not necessarily speak the same language. As a result, an information gap exists for many surgeons on some of the practical features of the equipment they use. This is unfortunate, because you do not need to be an engineer to intelligently operate a phaco machine any more than you need to be a mechanic to drive a sports car. You do, however, need a basic understanding of how the machines work and some familiarity with operating their controls. That is the goal of this chapter, and you can relax in the promise that there will be no mathematics or formulas anywhere. Try not to skip around, however, because the concepts are developed in a sequential and, hopefully, logical order.

HOW TO SET THE DIALS

One of the difficulties in writing a chapter on how to set the dials is that at the time of this writing there are at least nineteen different phaco units on the market. Each uses one of three different pump designs (peristaltic, diaphragm, or venturi) and has significantly different design features. On the other hand, all machines have in common a variety of choices on how to set the power, flow, suction, and infusion bottle heights. It is therefore critical that every surgeon understand the effects of each of these parameters, how they interrelate, and in total how they determine the surgical environment we work within.

Regardless of design, all phaco machines are faced with the same technical problems. We will start by examining the nature of these problems and the ways that one type of machine attempts to solve them. We can then begin to discuss differences in machines and develop concepts that allow us to intelligently control any type of unit.

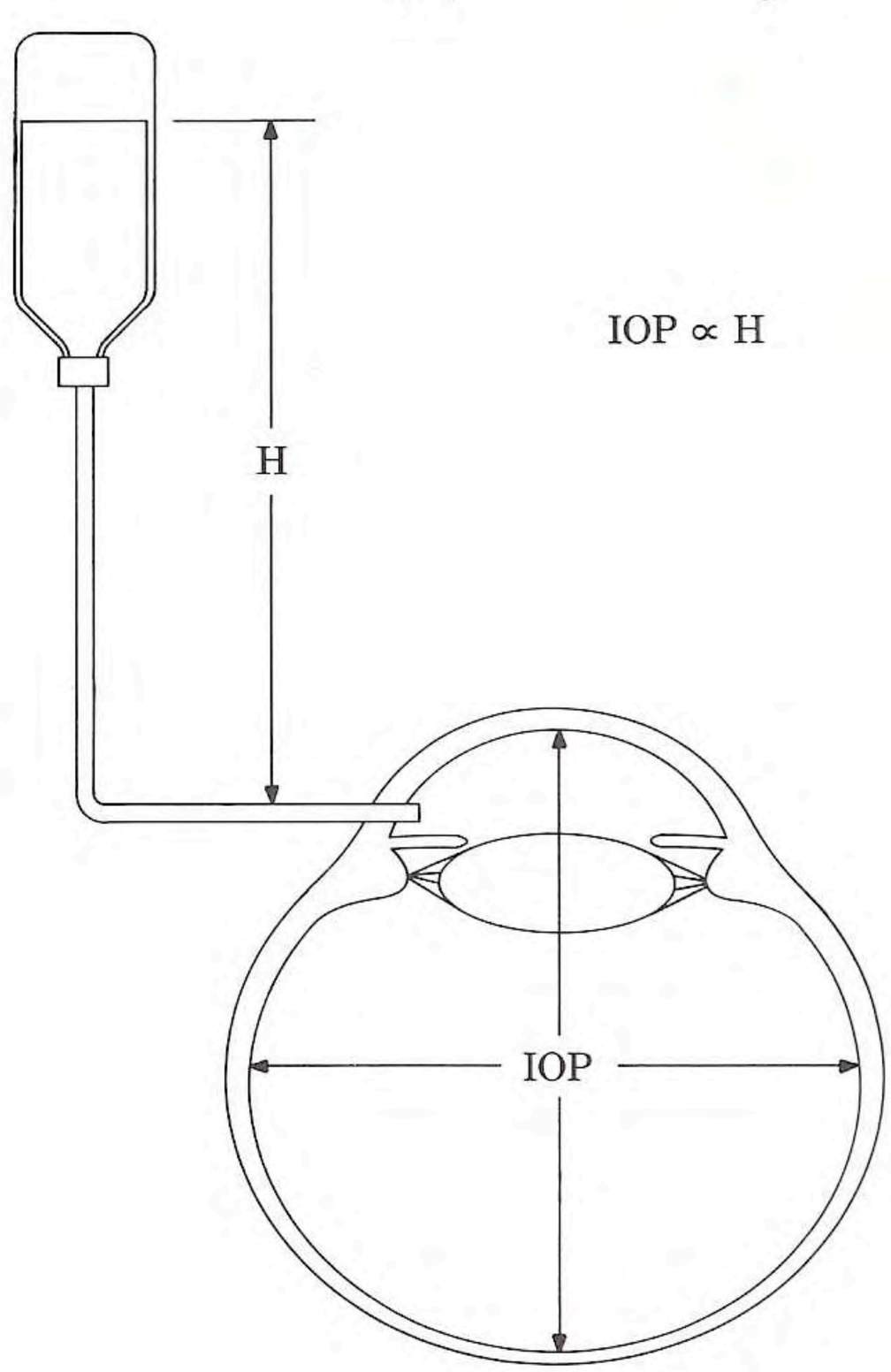
All phacoemulsification is carried out between two delicate structures: the corneal endothelium and the posterior capsule. A deep anterior chamber maximizes the distance between these two structures and increases our margin for safety. A deep anterior chamber, however, is of little value if the posterior capsule unpredictably moves forward, risking contact with our instruments. The goal, therefore, is to maintain not only a deep but also a *stable* anterior chamber. In principle this depends quite simply on maintaining a *constant* intraocular pressure. If during surgery the pressure within the eye suddenly decreases, the vitreous moves forward with the posterior capsule and iris diaphragm. The cornea may indent. Aside from the obvious risks to these structures, more subtle dangers may threaten patients with

abnormalities of the choroid or retina; for example, retinal breaks in high myopes, or subretinal hemorrhage in patients with macular degeneration. Stability of intraocular pressure is therefore critical, but at what level?

In general, a very soft eye will not maintain a deep anterior chamber and is therefore undesirable. On the other hand, an overly pressurized eye introduces stress forces onto the posterior capsule, which predispose it to tearing and then will increase any tear should one occur. High intraocular pressures also tend to hydrate the vitreous and can cause vitreous bulging, especially in prolonged cases where a capsule has been broken. The ideal intraoperative pressure is probably around 30 mm Hg or slightly higher than physiologic. For the brief duration of surgery, this poses no risk to the optic nerve or retinal vessels and is adequate to keep the posterior capsule back without inducing any excessive stretch forces. To examine this further, a model is needed.

In a simplified system where an infusion bottle is connected to the anterior chamber by a watertight incision, the intraocular pressure depends entirely on the height of the bottle (Figure 2-1). If

Figure 2-1. In a simple closed system, intraocular pressure is controlled entirely by infusion bottle height.



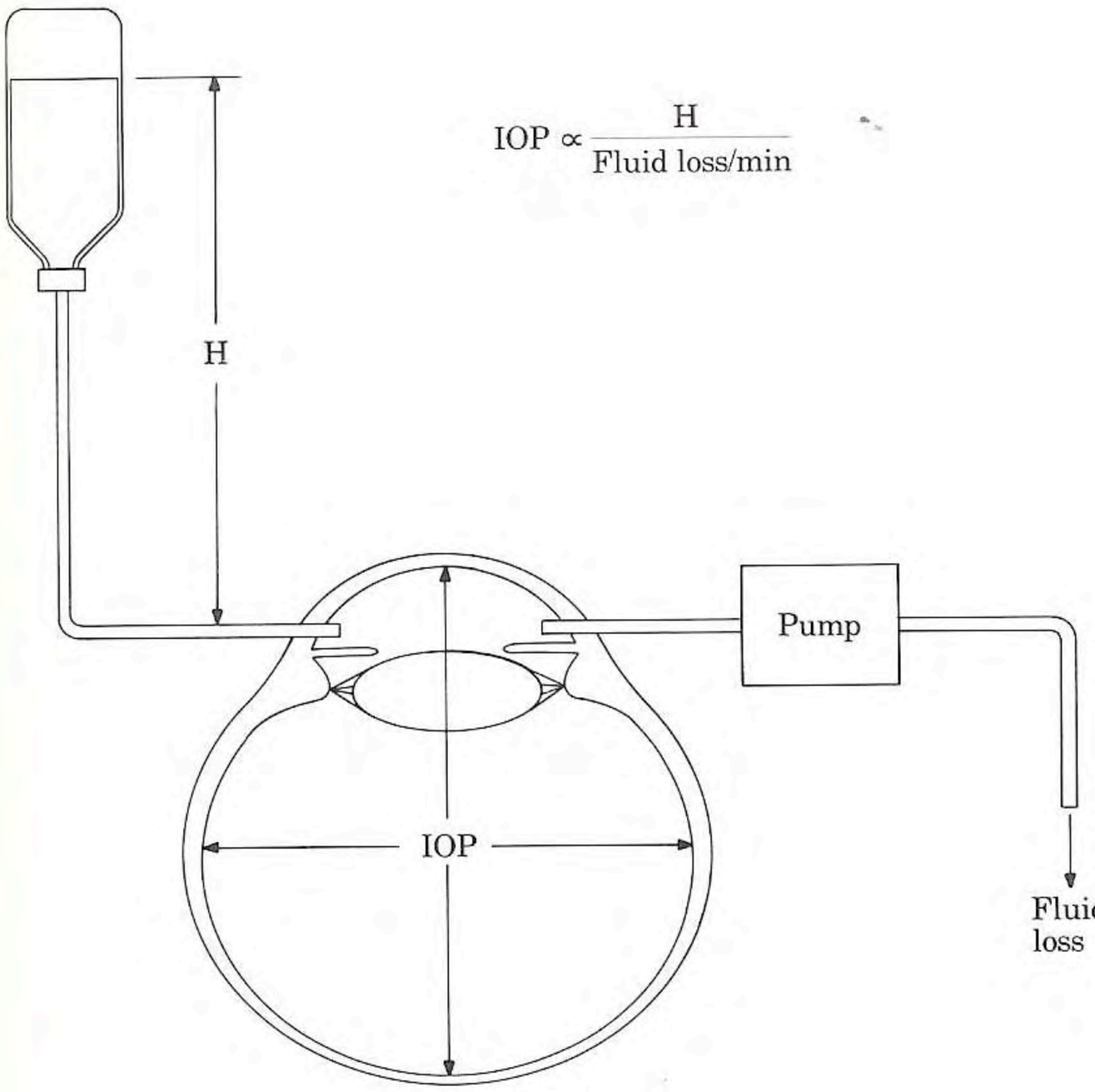


Figure 2-2. The effect of infusion bottle height on intraocular pressure is reduced in proportion to the rate of fluid loss from the eye.

we begin to pump liquid from the eye, the intraocular pressure will still vary directly with the bottle height but inversely with the rate of fluid loss from the pump (Figure 2-2). If the evacuation rate remains constant, the intraocular pressure will remain constant as long as we don't move the bottle. We can then simply adjust the bottle up or down to obtain the desired intraocular pressure, and we have established the ideal environment with a deep and stable anterior chamber. Two critical conditions were imposed on this model. First, the wound must be watertight; and second, the evacuation rate must remain constant.

In reality there is always some leakage at the wound, but if this is small and constant in amount the effect is negligible. For this reason some manufacturers offer a solid infusion sleeve (Figure 2-3), which permits tighter wounds with less leakage. (They offer the additional advantage of thermal protection at the wound and protection

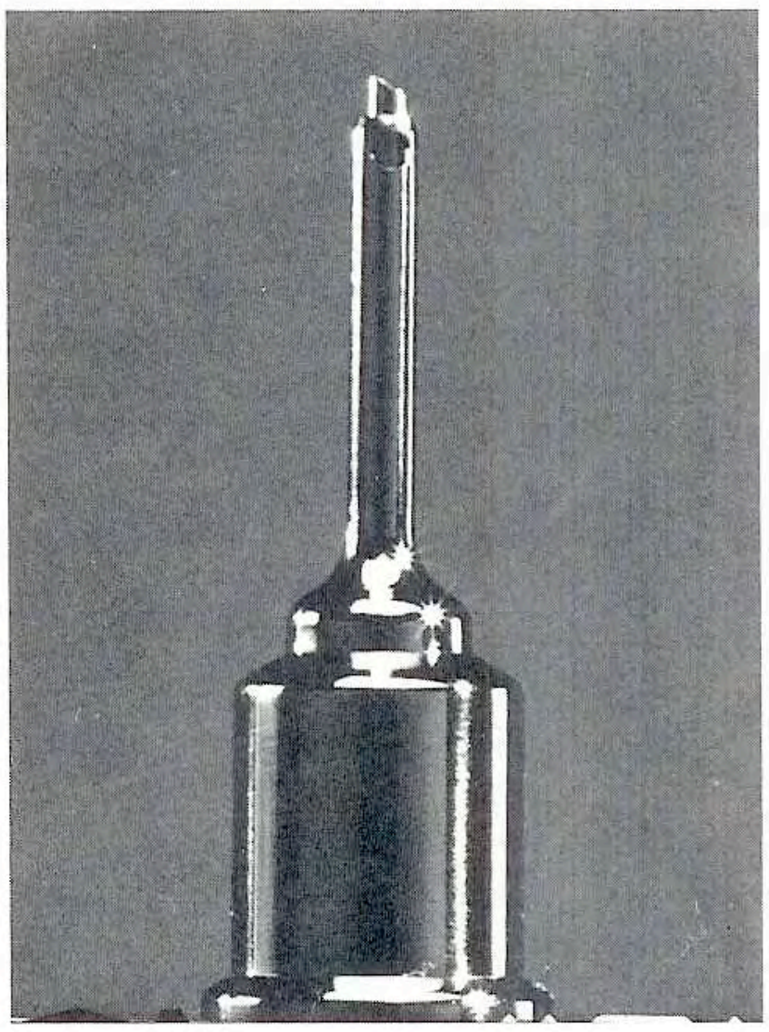
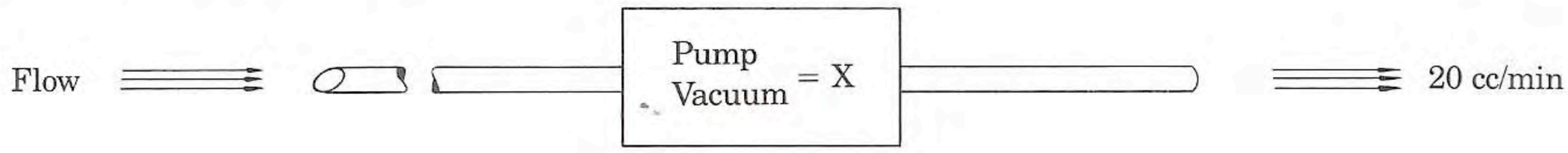


Figure 2-3. Solid infusion sleeve (Surgical Design).



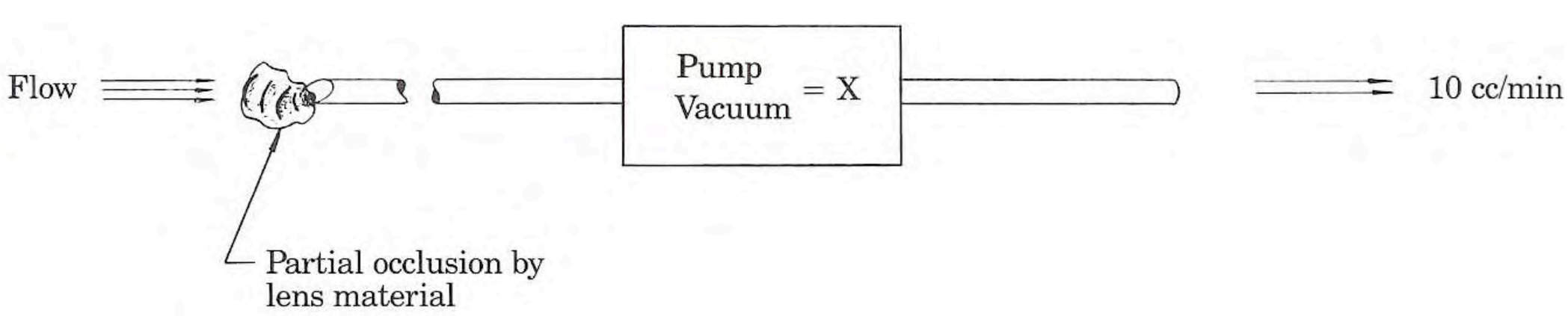


Figure 2-4. A smaller effective port opening creates increased resistance to flow.

from transverse ultrasonic radiation to the cornea.) Flexible infusion sleeves require larger incisions to prevent inadvertent crimping as the tip is maneuvered within the eye.

Any crimping would reduce the infusion, causing a momentary drop in intraocular pressure and some degree of collapse. Assuming then that we minimize wound leakage, the remaining factor essential to our model is a constant evacuation flow rate.

Imagine a peristaltic pump running at a set speed evacuating 20 cc/min from an eye (Figure 2-4). If the evacuation port becomes partially occluded with lens material, its effective opening is smaller, so resistance to flow increases. The evacuation rate would then tend to decrease (for example, 10 cc/min) and fluctuate as the degree of tip occlusion varies. But in order to maintain our goal of constant intraocular pressure, the flow rate must remain constant. The model system must then somehow sense the occlusion and compensate by increasing pump speed to maintain a constant flow rate. In practice this can be accomplished by placing a sensor or transducer in the evacuation line before the pump (Figure 2-5). The transducer's job is to sense any drop in flow rate and compensate by feedback to increase pump speed. (In reality the transducer actually senses pressure changes that reflect the flow rate, but this is overcomplicating our model.)

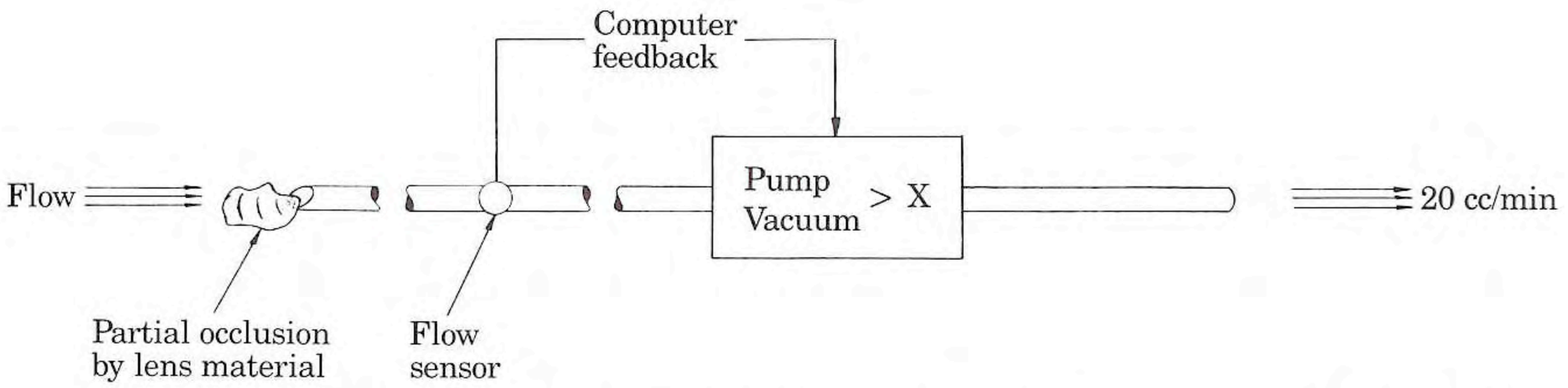


Figure 2-5. To maintain a constant flow the pump adjusts vacuum levels to respond to resistance changes at the instrument tip.

SURGE PREVENTION

Now that we have solved the problem of partial occlusions, what about when the tip is totally occluded (Figure 2-6)? At that moment the flow rate is zero, which is nevertheless a constant rate, so intraocular pressure will also be constant and there is no problem. What happens next, however, is that the evacuation pressure inside the tip builds up and a pressure differential exists across the evacuation port. In other words, the pressure in the eye is greater than the pressure inside the tip and only lens material separates the two. If this is suddenly drawn in, the high pressure in the eye must equilibrate with the low pressure in the tip, resulting in a surge of fluid from the anterior chamber into the tip (Figure 2-7). This results in a sudden drop in intraocular pressure

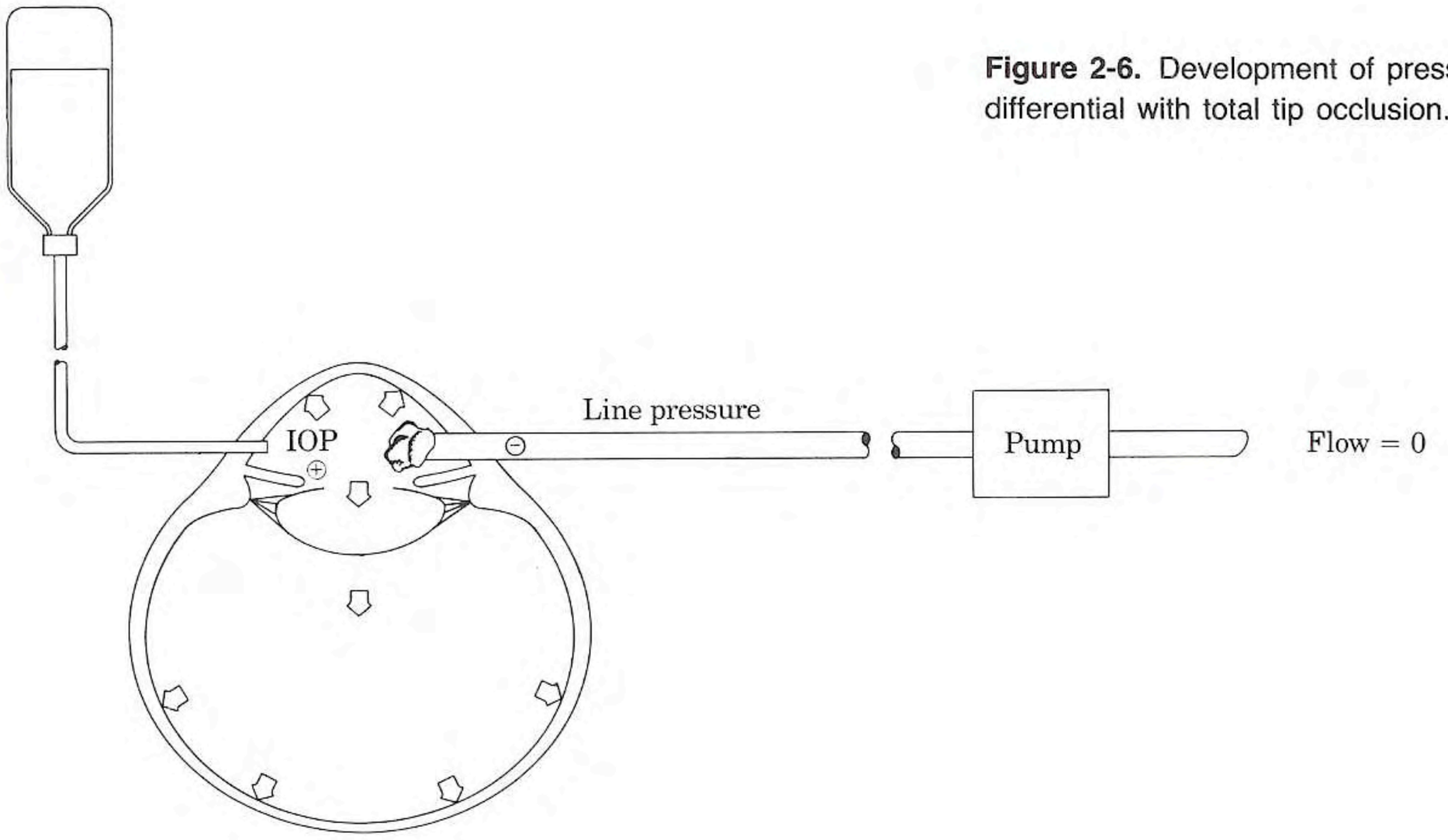


Figure 2-6. Development of pressure differential with total tip occlusion.

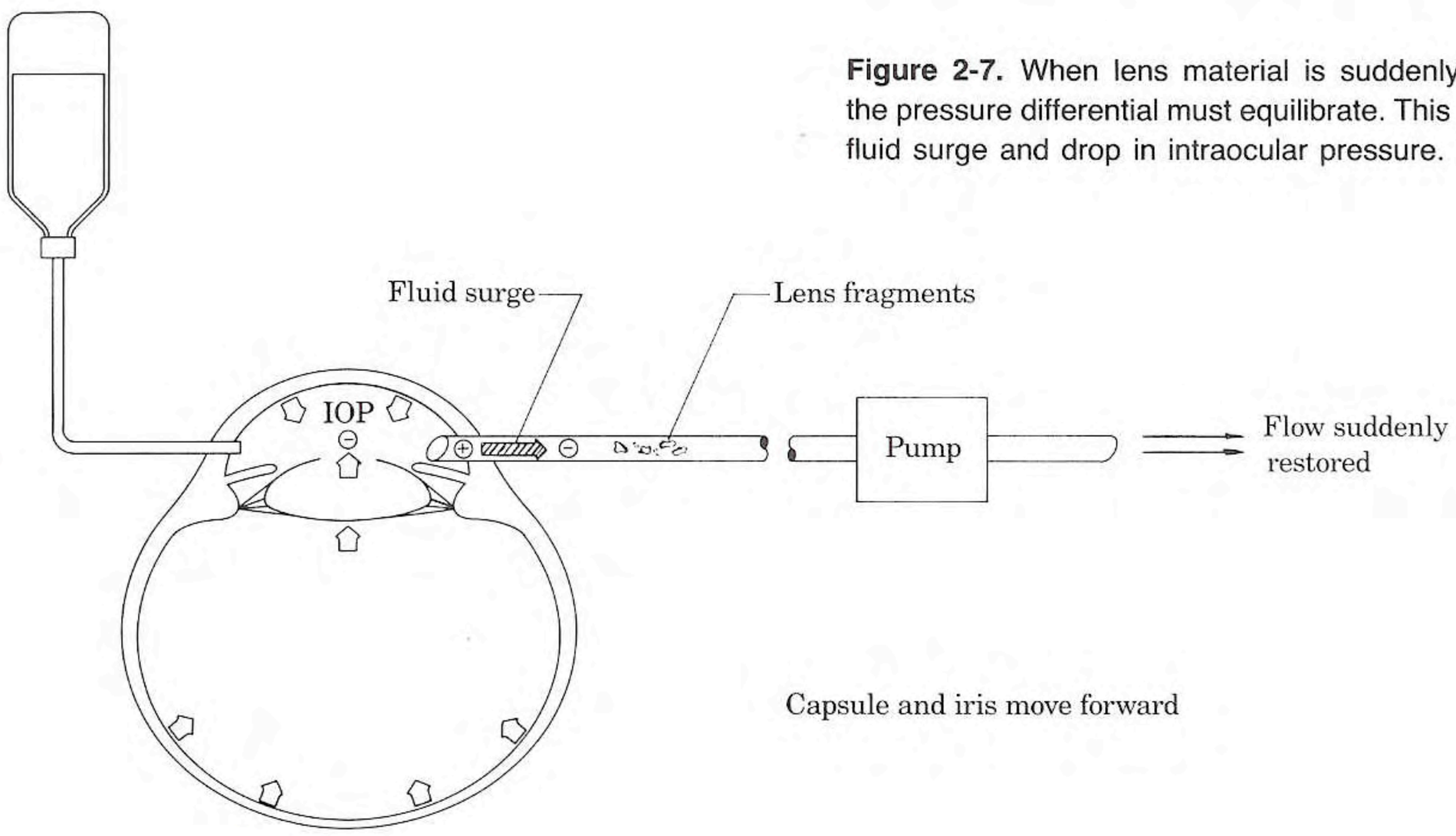


Figure 2-7. When lens material is suddenly aspirated, the pressure differential must equilibrate. This produces a fluid surge and drop in intraocular pressure.

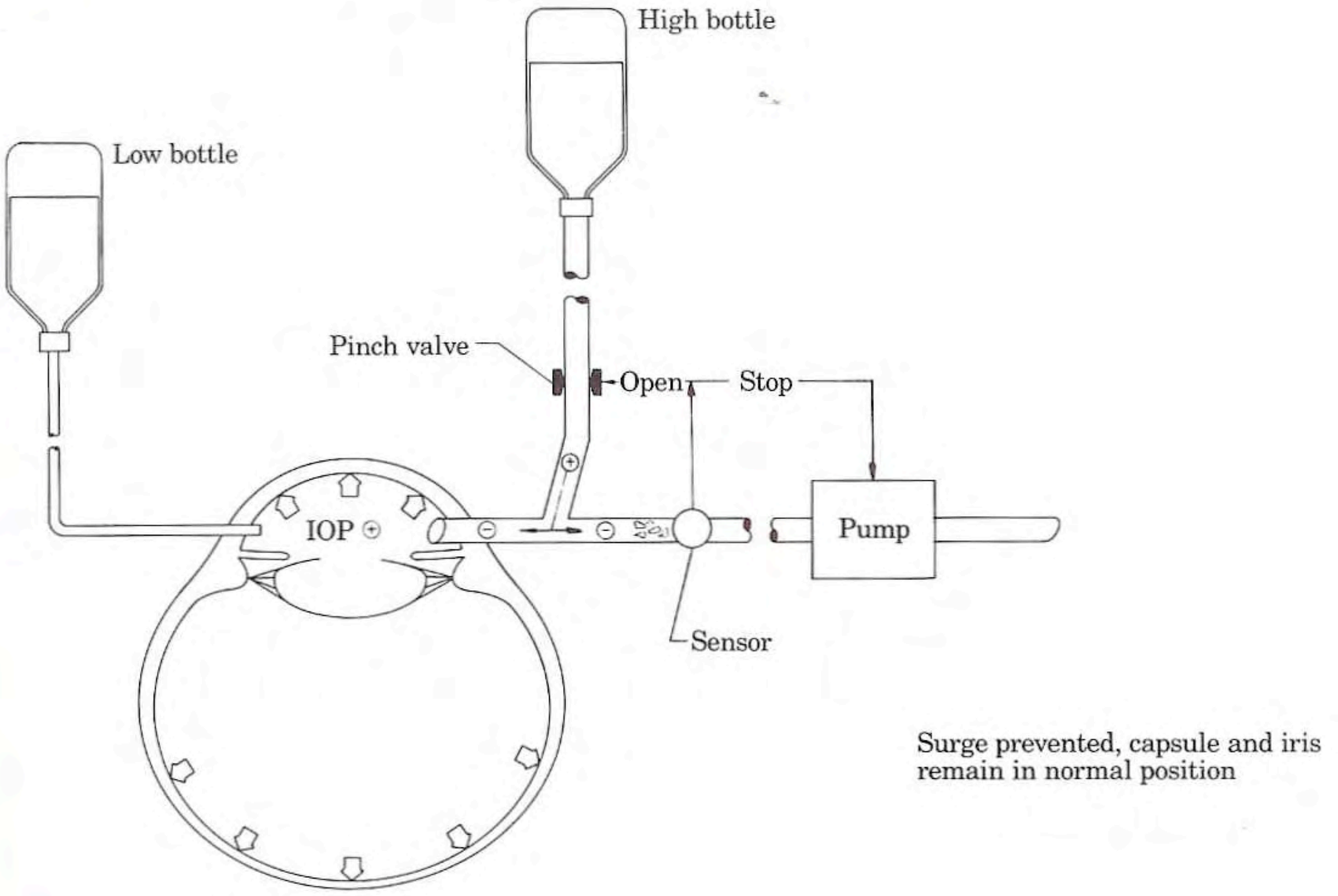


Figure 2-8. Surge prevention mechanism.

and some degree of collapse. We would like our transducer to sense the surge and make a correction, but how? Increasing pump speed is obviously counterproductive and stopping the pump only eliminates further buildup of negative pressure in the tip. We need to compensate by instantaneously raising the pressure inside the tip to at least the same pressure as exists within the eye. If this can occur fast enough, the surge is aborted and the collapse is prevented. At first glance the solution might be to have the pump reverse itself, but in practice the solution is to stop the pump and vent a second bottle of fluid (higher than the infusion bottle) directly to the tip (Figure 2-8). This, at least in theory, then describes a model capable of providing a constant stable anterior chamber by automatically altering pump speed and evacuation pressures to maintain a constant evacuation rate and, therefore, a constant intraocular pressure.

PUMPS

Why was a peristaltic pump chosen for this model? A peristaltic pump is also referred to as a "constant flow" pump. It consists of a wheel with protruding bearings that constrict a liquid-filled tube (Figure 2-9). As the wheel rotates, the

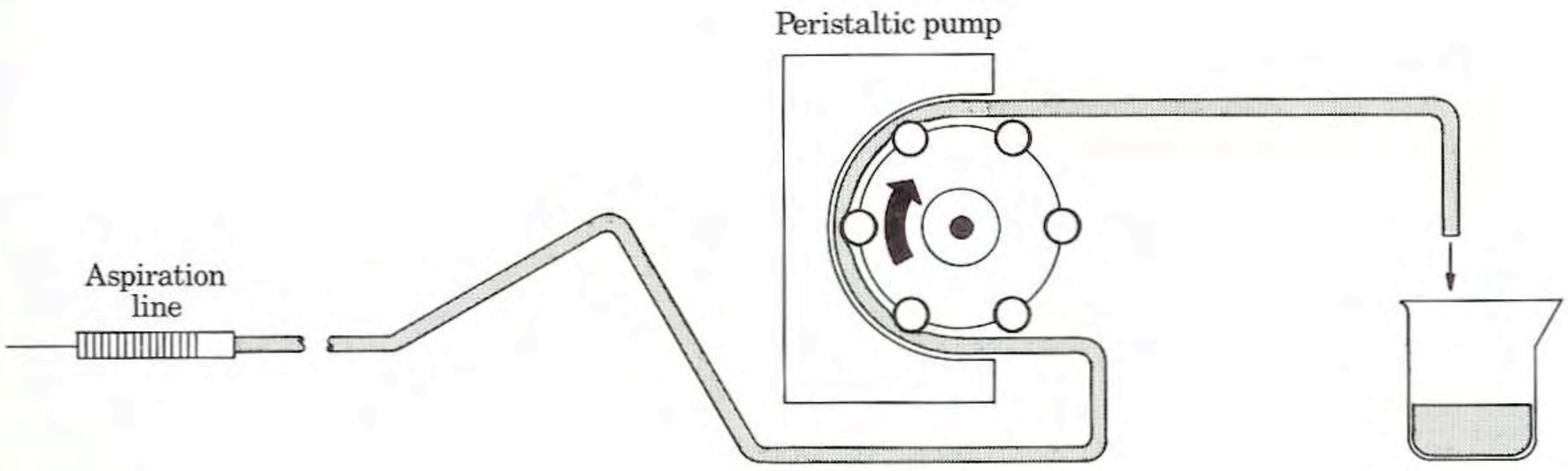


Figure 2-9. Peristaltic pump.

point(s) of constriction moves along the tube, "milking" a constant volume of fluid through the segment of tubing it contacts. The rate of flow is therefore constant for any constant rate of wheel rotation. If our goal is to maintain a constant intraocular pressure, we must maintain a constant flow rate; a peristaltic pump is well suited for this task.

Venturi and diaphragm pumps operate by varying evacuation rates to accommodate changes in pump pressures. They may be thought of as "constant vacuum" pumps. In a diaphragm pump, a flexible membrane (or piston) is used to pull fluid into a chamber through a one-way valve (Figure 2-10). With the compression stroke, the fluid is then pushed out of the chamber through another valve. The piston is driven by an electric motor, and its speed is controlled by the surgeon's foot pedal. In practice, the pump may be connected to a collection jar within which suction is maintained by the pump's evacuation of air (Figure 2-11).

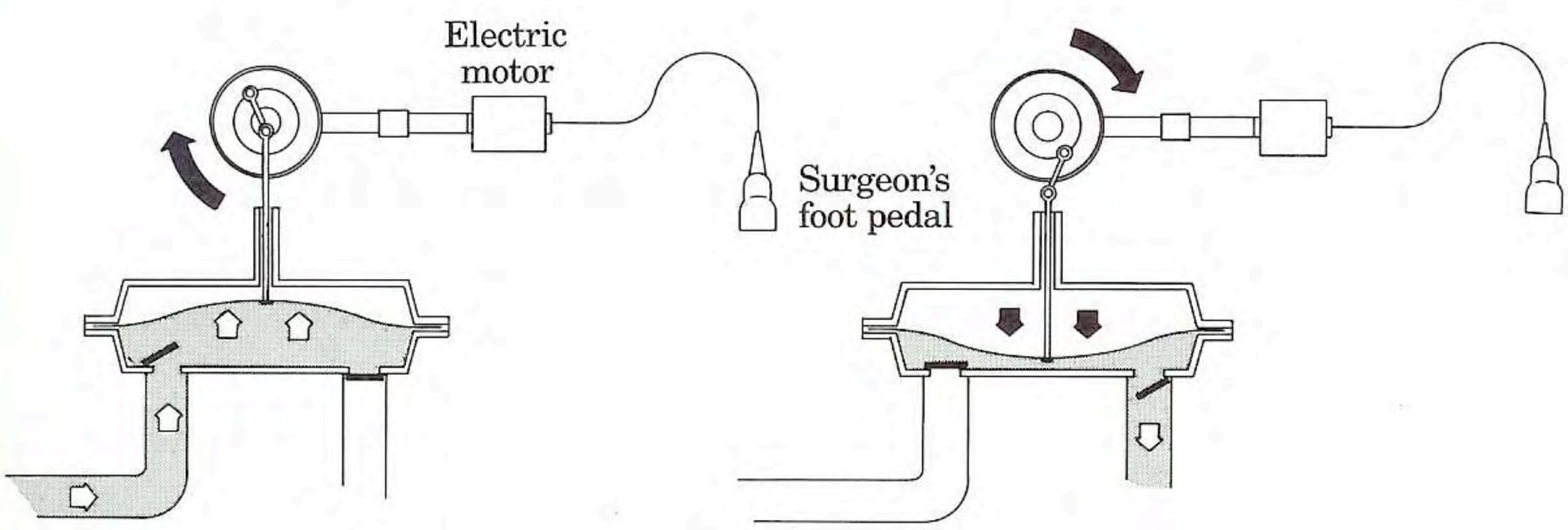


Figure 2-10. Diaphragm pump.

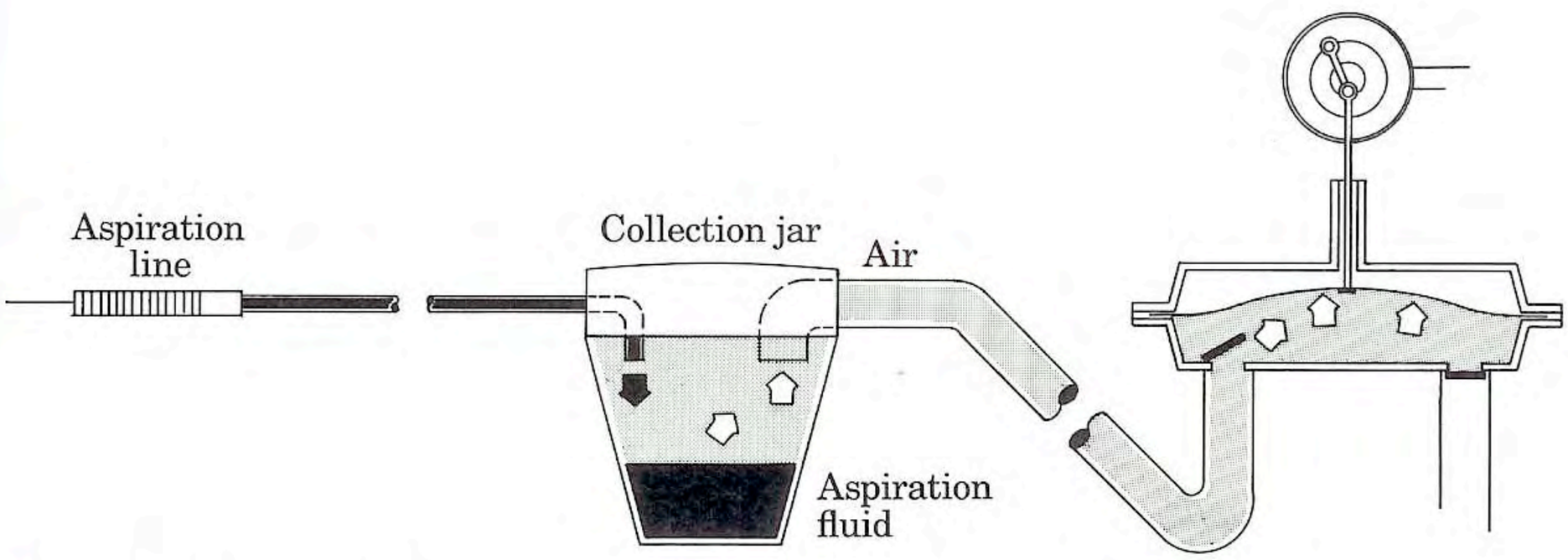


Figure 2-11. Diaphragm pump.

Venturi pumps operate by the same principle as the aspiration attachment on chemistry lab faucets. Instead of running water, compressed gas is directed past the aspiration line, thereby creating a vacuum. The surgeon's foot pedal controls an iris diaphragm that modulates the gas flow and, therefore, the vacuum level of the machine (Figure 2-12). At very low levels, the venturi's vacuum response curve is more linear than that of a diaphragm pump. For the anterior segment surgeon this is of little significance; and within this text they shall be considered equivalent.

It should not be inferred that venturi or diaphragm pumps cannot be used to obtain excellent results, but the surgeon must be aware of the greater potential for capsule movement and develop his technique accordingly. A peristaltic pump, for example, may take 15 seconds to achieve maximum vacuum level when using low flow rates, while a diaphragm pump may only take 3 to 5 seconds. This more gradual rise time gives peristaltic pumps the reputation of being "more forgiving," while sudden and potentially dramatic suction changes may make diaphragm pumps feel "more responsive." This diaphragm characteristic may in fact offer certain advan-

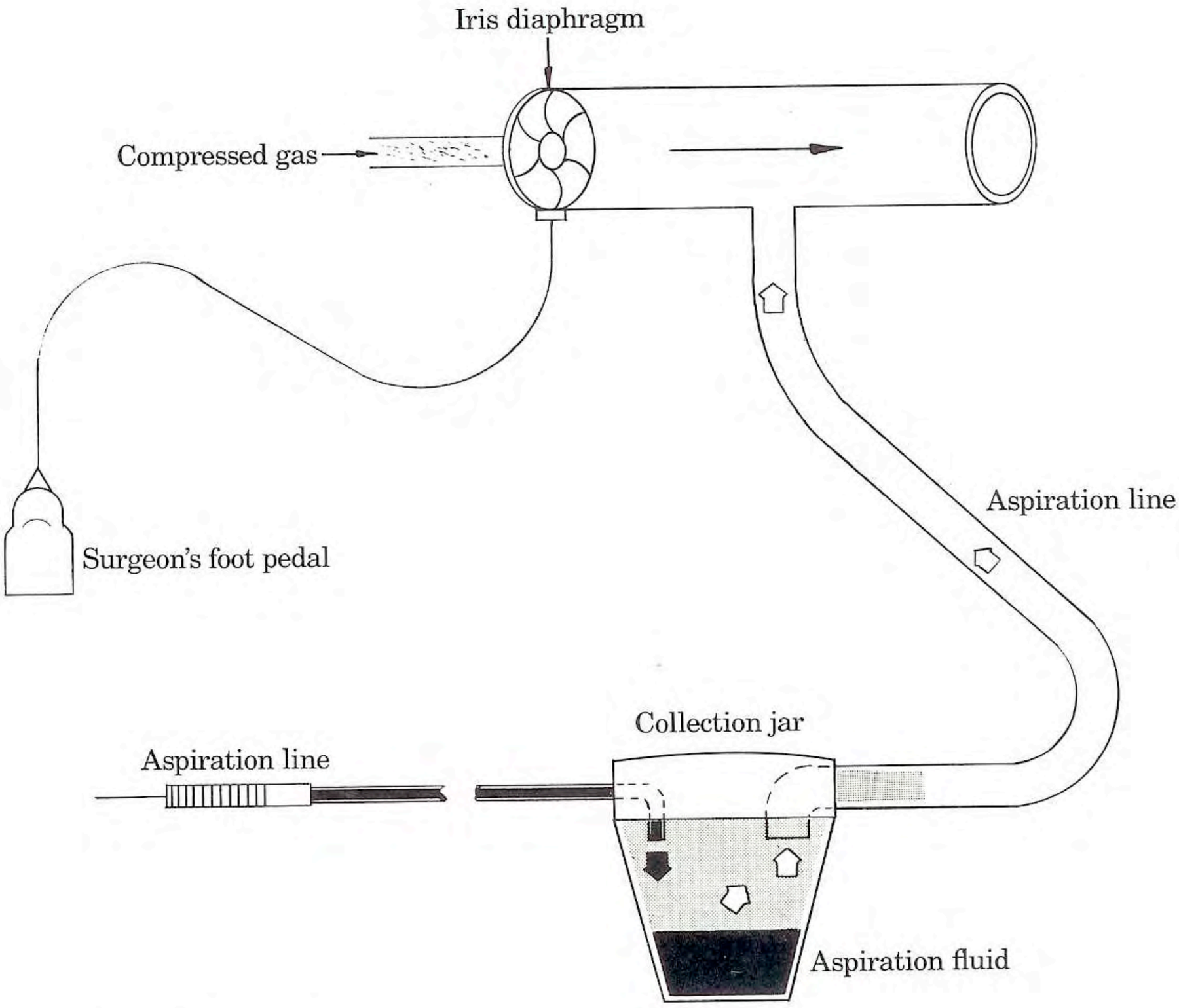


Figure 2-12. Venturi pump.

tages for the vitreoretinal surgeon, but for phacoemulsification it introduces certain liabilities. Constant flow rate cannot be provided and intraocular pressure will constantly vary.

VENTING

Only one existing phaco unit has a surge prevention mechanism as previously described; for the others venting is activated upon release of the foot pedal. This momentarily opens the evacuation line to atmospheric pressure at the level of the console and relieves residual suction that exists in the tubing (Figure 2-13). It will release tissue that is drawn *against* the aspiration port, but it will not reflux material aspirated *into* the port nor will it equilibrate a pressure differential that exists in a surge situation. Since the venting action is only momentary, residual line suction created by high vacuum levels may not be totally relieved. This is generally of more concern with diaphragm pumps, and it may be advisable to use lower vacuum limits during anterior segment procedures with these units. Using lower bottle heights will also help minimize pressure differentials that might lead to fluid surges or incarceration of unwanted tissue within the aspiration port.

It should be mentioned here that any machine (regardless of pump design) that does not have a surge prevention mechanism may depend on incisional flow to compensate for fluid surges; in other words, when fluid is suddenly drawn into a port after occlusion is broken, the fluid that is normally lost through a leaky wound may become available to minimize anterior chamber collapse. In a sense it acts as a fluid reserve but can only safely compensate for small surges from small pressure differentials. This is one reason that most machines can only safely recommend −40 to −75 mm Hg of suction during phaco.

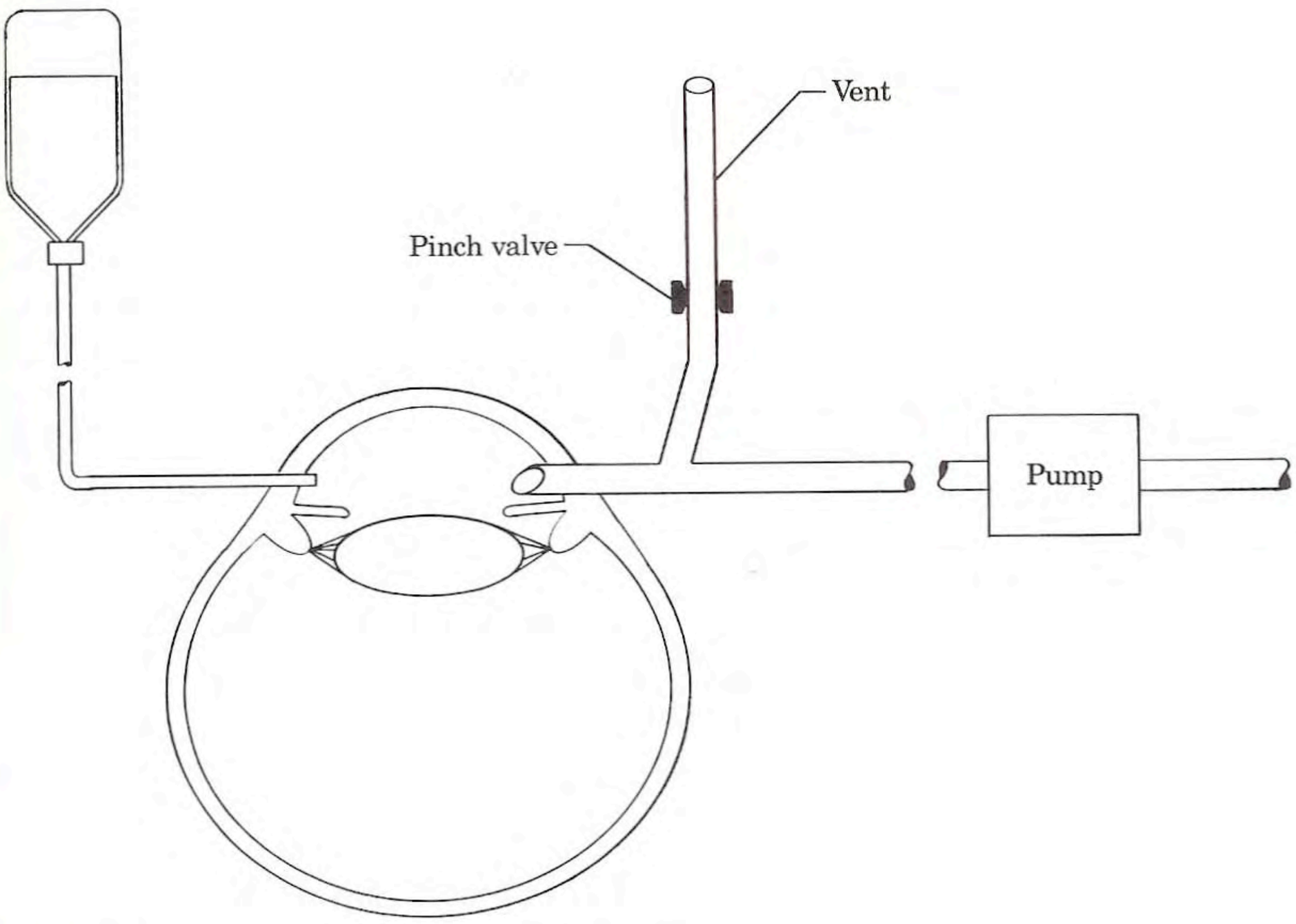
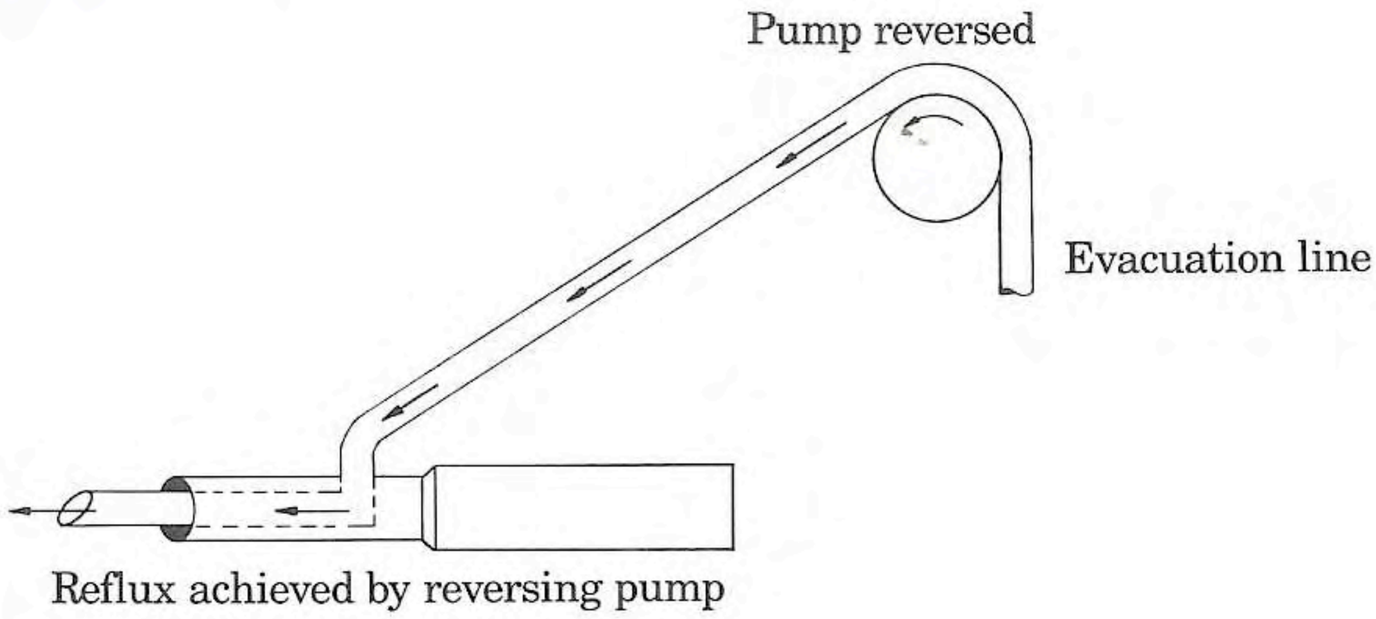


Figure 2-13. Venting relieves residual suction in the line. It is activated by the foot pedal and does not prevent fluid surge.



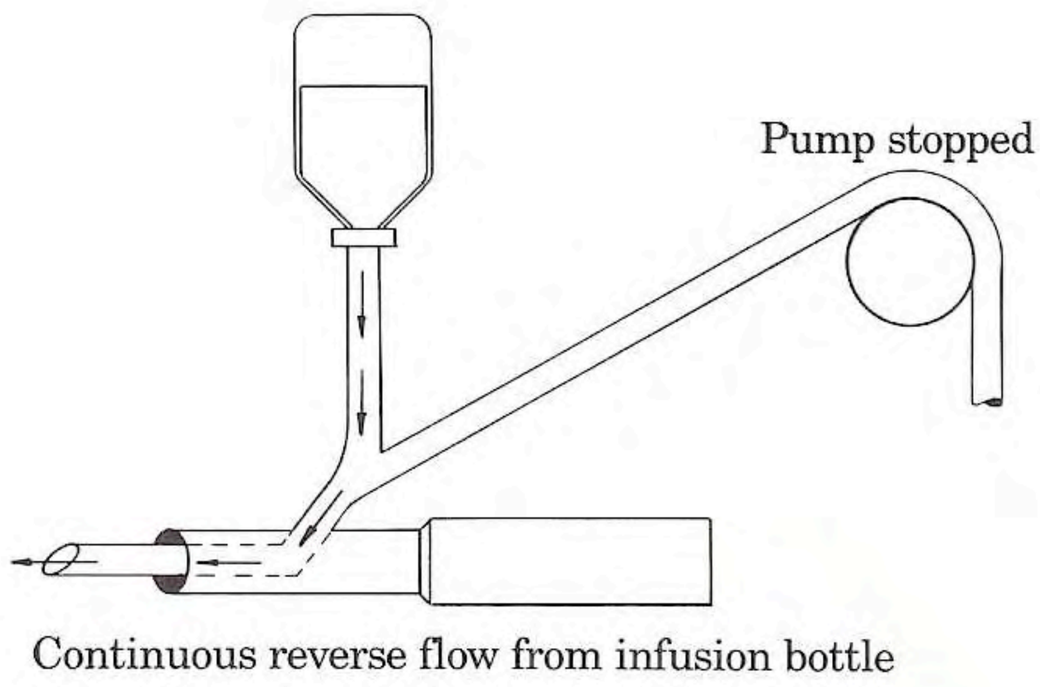


Figure 2-14. Mechanisms for intermittent versus continuous reverse flow.

REVERSE FLOW (REFLUX)

Several machines now offer the ability to reverse the direction of flow through the evacuation line by activating a separate pedal or switch with the surgeon's foot. This is accomplished either by reversing the direction of a peristaltic pump or by simultaneously closing the evacuation line and opening a second infusion line connected to the handpiece (Figure 2-14). The latter design offers several advantages:

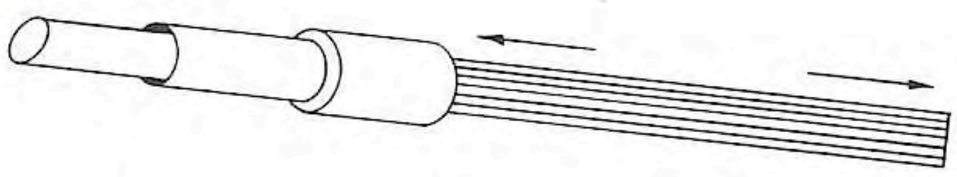
1. The reverse flow can be continuous as long as the foot pedal is depressed, thereby allowing its use for hydrodissection, nucleus delivery, and irrigation of the anterior chamber to dislodge nuclear fragments from beneath the iris or superior angle. It is also helpful for deepening the chamber when entering the eye.
2. The flow is from a sterile infusion bottle and does not "backwash" lens fragments back into the eye from the aspiration line.
3. The force of the flow is controllable by adjusting bottle height and cannot exceed safe levels.

Reverse flow generated by reversing pump rotation could potentially build excessive pressure within an occluded line, resulting in lens fragment projectiles endangering the eye. This type of system must therefore be either pressure limited or volume limited to avoid this threat, as well as excessive intraocular pressures.

As a result, this design is actually limited to a few seconds of operation and a few milliliters of volume during one reflux cycle. This is sufficient to reflux aspirated material but ineffective for hydrodissection or nucleus delivery requiring a continuous reverse flow mechanism.

ULTRASONIC POWER

The tip of the phaco handpiece is attached to a transducer, which is either a stack of metal plates (magnetostrictive) or crystal (piezoelectric). When properly stimulated, the transducer lengthens and shortens, causing the tip to move forward and backward at a specific frequency (Figure 2-15). The particular frequency varies with manufacturer and ranges from 27 to 64 kHz. Magnetostrictive transducers are stimulated by an electromagnetic field generated by a coil of wires wrapped around the handpiece, while the piezoelectric transducers require a direct electrical contact to the crystal. It is this basic difference and a relative fragility of the crystal that account for the contention that magnetostrictive transducers are more reliable with longer life expectancies. The particular frequency at which a given transducer operates is a design choice made by the manufacturer and not a limitation imposed by the type of transducer employed.



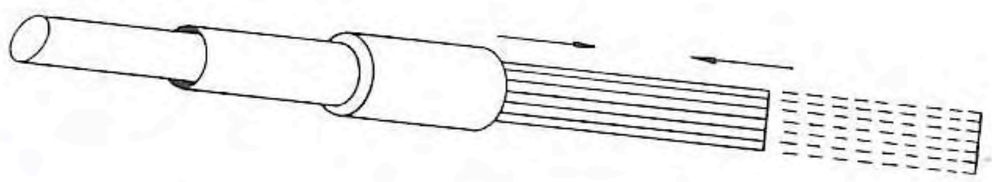


Figure 2-15. Magnetostrictive transducer lengthens when stimulated by magnetic field and springs back toward original length when the field is terminated.

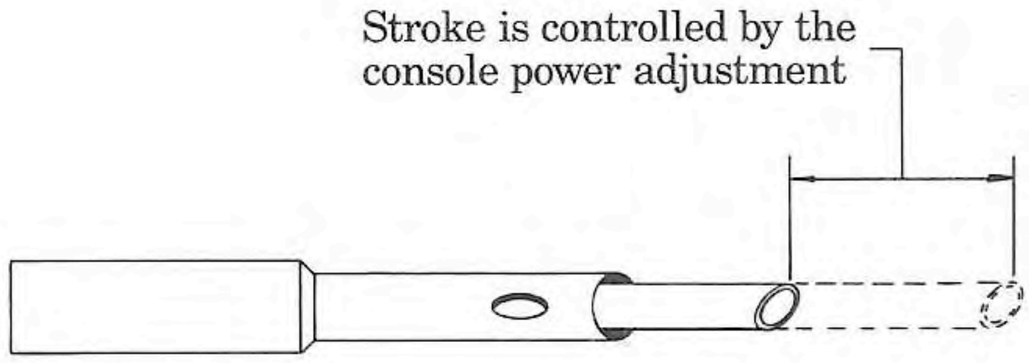


Figure 2-16

In terms of power, the method of creating vibrations is not as important as the actual frequency and stroke. It is the stroke or length of the tip movement during one cycle that we control with the power adjustment on our machines (Figure 2-16). How well the power adjustment translates into cutting efficiency is a bit more complex. It depends, for example, on the mass, shape, and sharpness of the tip, which determines the concentration of the applied force. The flow rate and suction levels may also influence how effectively we use our power, but this will be considered later. For now, suffice it to say that claims for higher frequencies equating to improved cutting efficiency have not been borne out. What appears to be more important is the ability of the handpiece to maintain its optimal resonant frequency throughout the surgical procedure.[1]

Resonant frequency is a characteristic of the size and mass of a vibrating body. Most machines provide automatic tuning prior to entering the eye to match the output of the ultrasonic generator in the console to the resonance of the handpiece. When the phaco tip engages a nucleus, however, the mass of the body (handpiece plus nucleus) changes. There is increased resistance to its motion, the resonance of the system changes, and the machine is in effect out of tune. This results in a significant drop in cutting efficiency. A few manufacturers (Table 2-1) have now in-

TABLE 2-1. EQUIPMENT SPECIFICATION

	ULTRASOUND			IRRIGATION/ASPIRATION			
COMPANY	MODEL	TRANSDUCER FREQUENCY, kHz	POWER	PUMP TYPE	VACUUM RANGE, mm Hg	FLOW RANGE, cc/min	IOP MAINTENANCE AUTOMATIC SURGE PREVENTION
Alcon	Master Series Ten Thousand	Piezoelectric 40 kHz	Linear control, panel control, linear pulse	Peristaltic (cassette-driven)	0–400	0–40	No
Allergan Medical Optics	Phaco Plus (Model 6000)	Piezoelectric constant self-tuning 46–47.5 kHz	Linear or panel control of continuous or pulsed power. Adjustable preset maximum levels.	Peristaltic	0–500	7–50	No
Optical Micro Systems Inc.	OMS Diplomate	Piezoelectric continuous autotuning 39 kHz	Footswitch linear, with adjustable maximum levels, or panel preset; continuous or pulse	Peristaltic	0–500	0–44	No
Phakosystems, Inc. 3M	CES 4000	Piezoelectric 40 kHz	Linear, adjustable levels	Diaphragm	0–508	0–17	No
Site Micro-Surgical Systems, Inc.	501–3560 Linear Pulse Phacoemulsification Module	Piezoelectric 64 kHz	Linear control, panel control	Diaphragm or peristaltic (cassette-driven)	0–540	2–30	No
Storz Surgical Systems	Premiere	Piezoelectric 28.5 kHz	Fixed, pulsed and linear, all adjustable	Venturi vacuum	0–550	0–40	No
Surgical Design Corp.	OCUSYSTEM II	Magnetostrictive continuous autotuning and amplitude maintenance 44 kHz	Linear foot switch control, panel control with or without pulse, auto or manual settings	Peristaltic	0–500	0–32.5	Yes
United Sonics, Inc.	Phaco 20/20 System I	Piezoelectric 27 kHz	Linear or panel with adjustable preset levels	Peristaltic (cassette-driven)	0–480	0–40	No
United Surgical, Inc.	Phacotron Systems Plus II	Cooled by forced air magnetostrictive 55 kHz	Linear or manual preset	Peristaltic	0–500	6–55	No

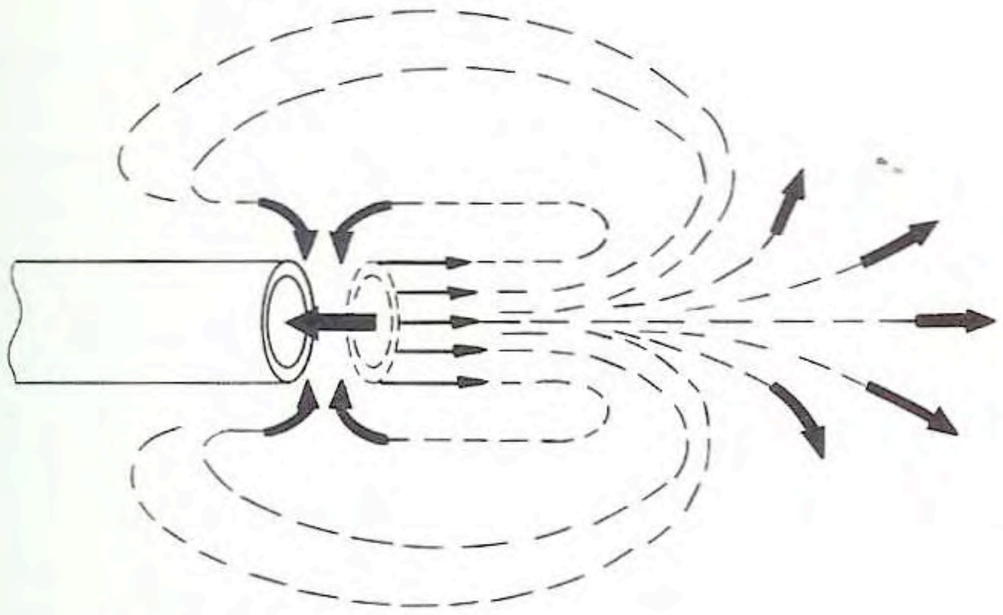


Figure 2-17. Cavitation.

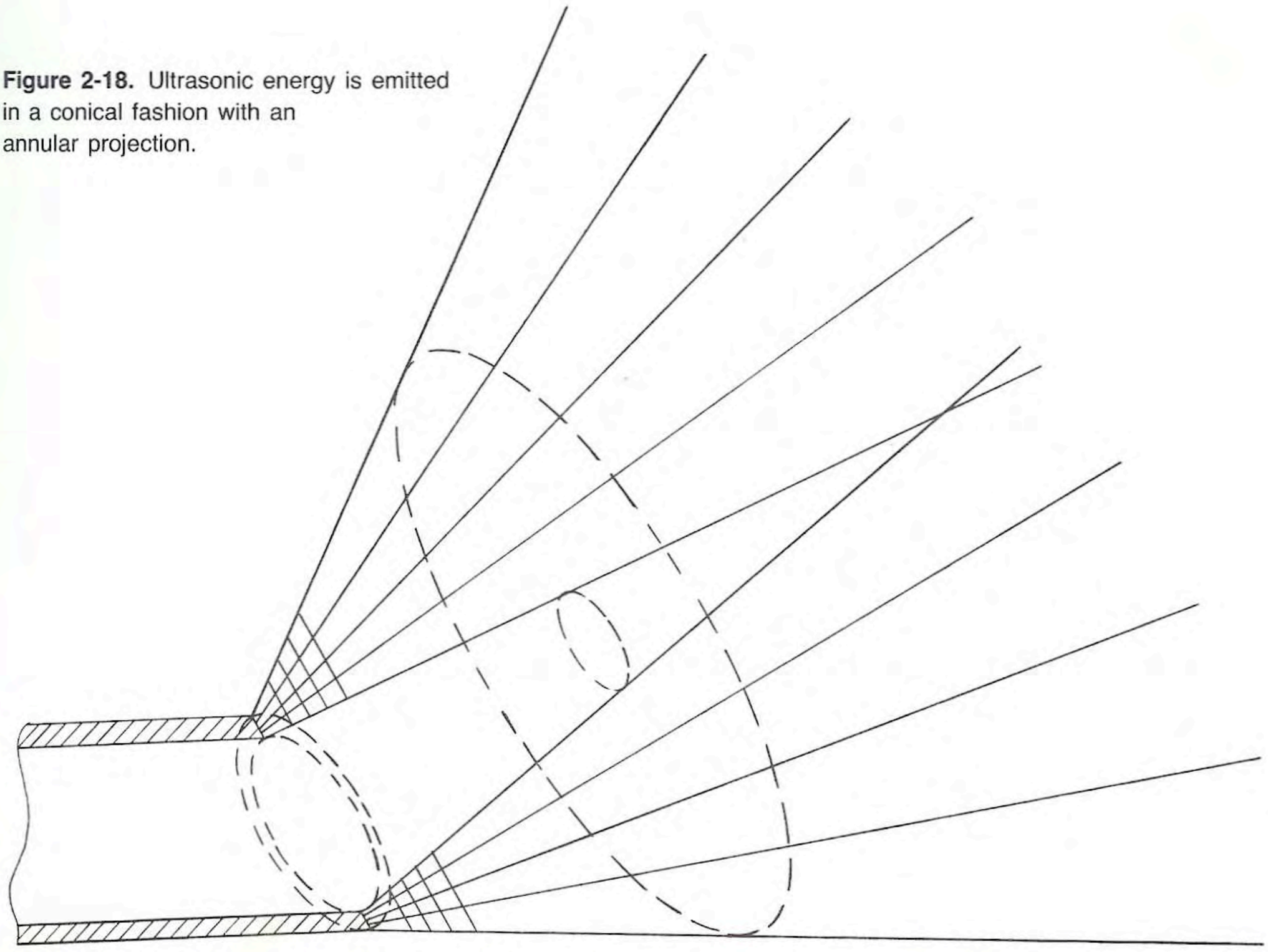
corporated a *continuous* autotuning function in their equipment. This enables the ultrasonic generator to constantly change its output to match the ever-changing resonance of the handpiece. Temperature changes in the handpiece can also affect resonance, and continuous autotuning not only corrects for this factor but also minimizes temperature elevation because of improved efficiency. This has a protective effect on the wound and the corneal endothelium.

Having so far discussed how ultrasonics are generated, let us now direct our attention to the nature of its power. Its ability to perform destructive work comes from several events:

1. The mechanical impact of the tip against the lens at the end of the stroke.
2. The shock of the acoustical wave transmitted through fluid in front of the tip.
3. The impact of fluid and lens particles pushed forward in front of the tip (which can reach velocities up to 72 km/hr).
4. Cavitation: At the end of the forward stroke, the tip has imparted considerable forward momentum to the fluid and lens particles in front of it. When the tip retreats, the fluid can not follow, and a void is created in front of the tip. This void is collapsed by the implosion (cavitation) of fluids from the side of the tip. This creates an additional shock wave (Figure 2-17).

It is important conceptionally to realize that power radiates in a conical fashion in front of the tip (Figure 2-18). Most manufacturers avoid a

Figure 2-18. Ultrasonic energy is emitted in a conical fashion with an annular projection.



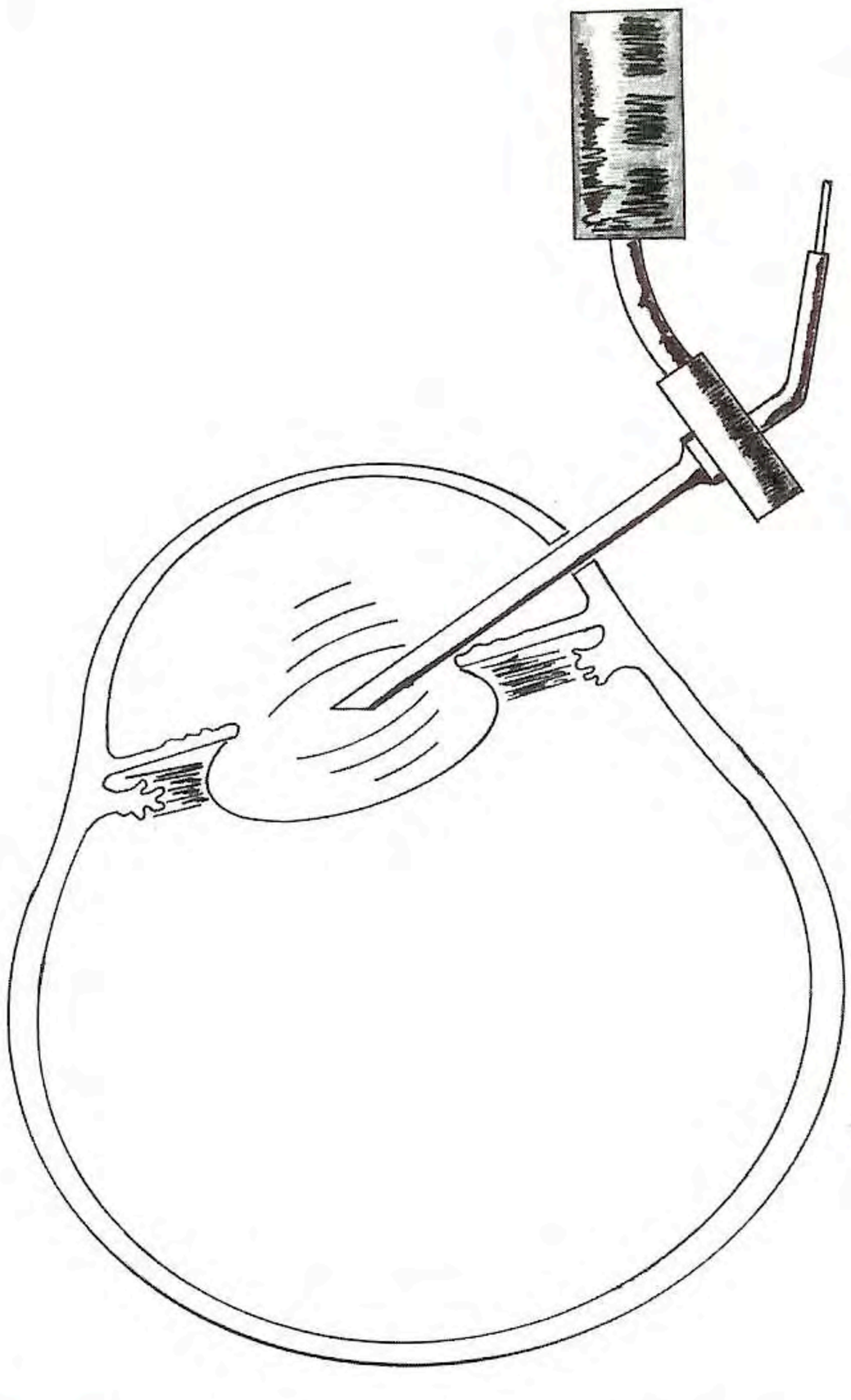


Figure 2-19. J. Shock tip. A decentered mass sends transverse (flexural) vibrations throughout the globe.

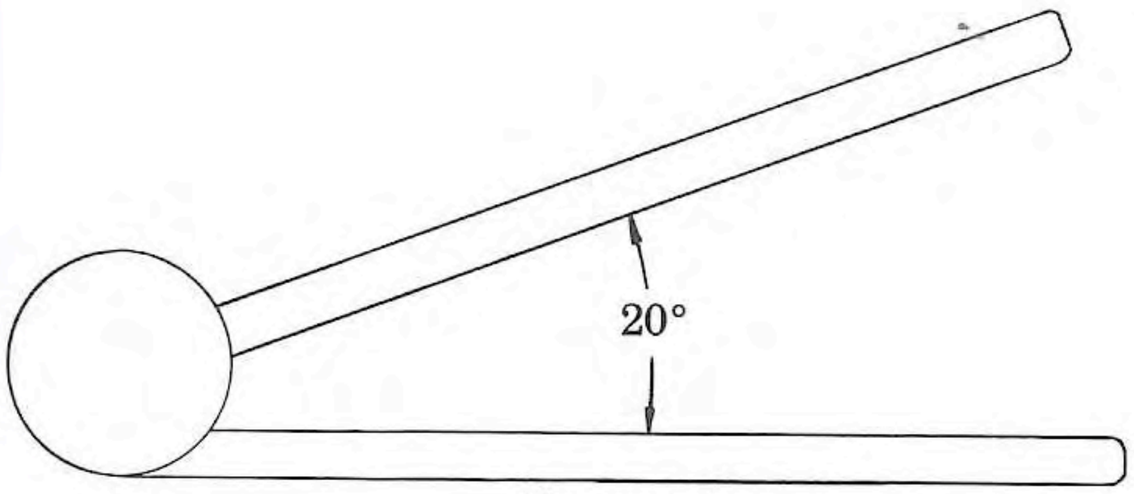
decentered tip mass that would result in transverse or flexural vibration that would send ultrasonic energy unnecessarily throughout the globe (an exception is the J. Shock tip) (Figure 2-19). We may therefore visualize the tip as aiming energy in the direction we point it. This energy becomes attenuated in aqueous as it moves away from the tip, and a nucleus mass is very effective in dampening it. It therefore follows that to protect corneal endothelium we should ideally work as far from it as possible, try to keep the tip pointing posteriorly,[2] and use bursts of ultrasonic energy only when the tip is in contact with a mass.

Sculpting in the posterior chamber meets all these criteria, and it is generally recognized for its safety in terms of the cornea. At some point in the procedure, however, many surgeons find it necessary to partially deliver or tilt the nucleus to complete the emulsification. If we bear in mind the characteristics of ultrasonic power, certain strategies will make more sense than others.

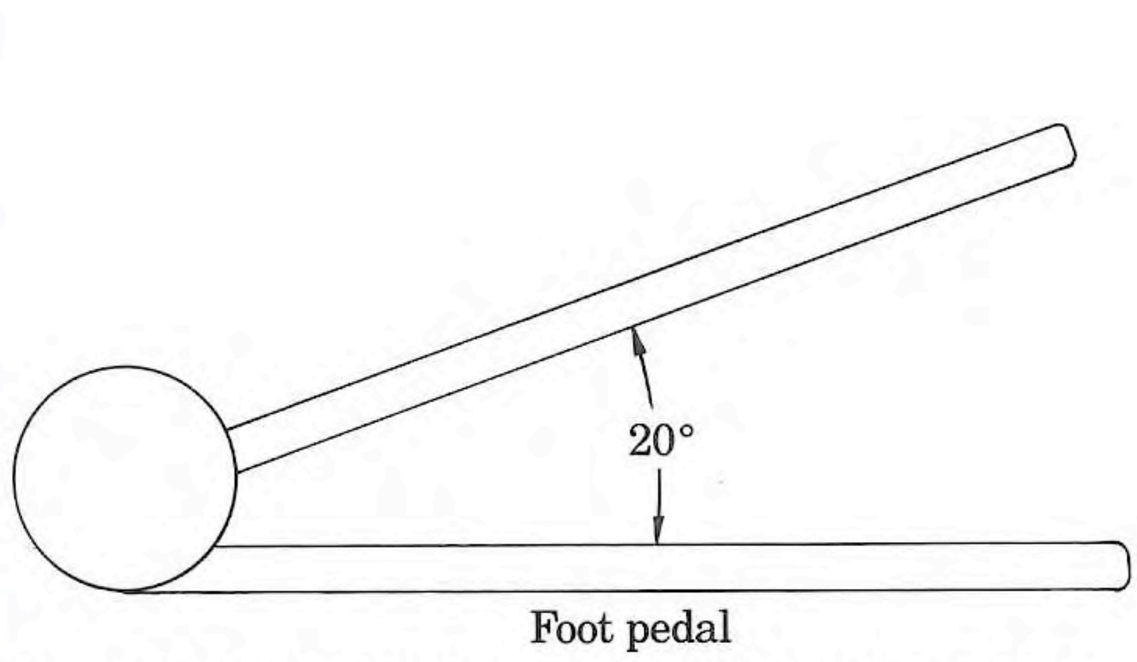
For example, working in the posterior chamber is ideal, while phaco in the iris plane is preferable to working in the anterior chamber. Using a two-handed technique allows the surgeon to control the nucleus mass against the phaco tip before engaging power. Positioning the tip on the underside of the mass creates a "shield" that protects the cornea. It should be stressed that studies by Pollack and Sugar[3] and Arentsen et al.[4] on endothelial damage have shown that direct contact by lens or instrument to the endothelium is considerably more damaging than exposure to ultrasonic power alone. Our first priority, therefore, is to never allow anything to touch the cornea. Secondly, ultrasonics should be directed as far away from the cornea as possible and always be dampened by direct contact with the nucleus.

Towards the end of a procedure, when dealing with small pieces of nucleus, most surgeons have experienced the frustration of seeing them bounce away from the tip. Remember that at high power a phaco tip can reach a velocity of 72 km/hr—pushing fluid and particles in front of it—and can effectively neutralize an evacuation flow of 12 cc/min. The solution, then, is to decrease the power or increase the flow rate. Since smaller masses have less damping effect on ultrasonic energy, decreasing the power is the better first choice because it also protects the cornea.

While salesmen and manufacturers still make claims regarding expanded power, it is probably safe to say all machines have more power than any prudent surgeon should use. Exactly where to set the dial will depend on the machine, the lens, and the surgeon. It should generally be as low as



Surgeon must depress pedal 6° to obtain useful power



Surgeon can use full 20° of pedal action with effective power

Figure 2-20

will efficiently perform the job at hand. Starting at 30 to 40 percent will adequately remove superficial cortex, and as you proceed deeper into the nucleus the power can be adjusted as needed. This approach has several advantages. First, higher powers are not used until sculpting has been initiated, allowing further distance between the tip and the cornea and a posterior direction to the power vector. Second, the surgeon must consciously decide to turn the power up, based on the observation of ineffective cutting. This is readily apparent as the nucleus is pushed by the tip rather than being cut by it. On the other hand, if we start with excessive power there may not be an obvious "cue" alerting us to turn the power down. Excessive power may lead to sudden, unpredictable movement of the nucleus with attendant danger to the capsule.

LINEAR POWER

Some machines now offer linear power control in the foot pedal. If this feature is used, it is important that the power range in the foot pedal correlate with the useful power range for a surgeon. If, for example, a given surgeon uses between 30 to 70 percent of a given machine's power for all cases from very soft to very hard nuclei, the pedal range should start at 30 percent and top off at 70 percent. This will maximize sensitivity of the pedal, because for a given amount of depression a smaller change in power will occur than if it had to range from 0 to 100 percent (Figure 2-20). It will also protect against inadvertent use of the extreme power settings. While these parameters are factory set, some manufacturers can adjust them to a surgeon's preference. A

potential danger still exists, however, that the surgeon will use more power than usual, unless a very discernible audible feedback is provided. Every gas pedal needs a speedometer.

PULSER POWER

With the pulser the emission of ultrasonic energy is interrupted at a specific rate, which may be set or adjustable depending on the manufacturer. When first developed by Banko and Freeman, the concept hinged on the idea that cutting efficiency would be enhanced by improved flow characteristics. As already mentioned, ultrasonics at the tip tend to oppose evacuation flow and tend to push lens material away. For the brief moment that ultrasonic energy is mute during the pulse mode, the flow towards the tip is unopposed and particles are more effectively drawn to the tip (Figure 2-21). In practice this results in a gentler, more predictable emulsification process. It is not as expedient for dense nuclei as continuous energy, but when removing a soft nucleus or nucleus shell the material moves very smoothly and predictably into the tip. This can be especially important if there is a tendency for posterior capsule movement, because a more consistent and predictable flow will provide greater stability in the anterior chamber. The same characteristics also make pulse power especially useful for endocapsular maneuvers when working with softer material near the capsule. A pulse rate of approximately 30 per second works well in the author's experience

COMPONENTS OF FLOW

In phacoemulsification there are three types of flow that require consideration. *Infusion* is the flow from the bottle through the handpiece into the eye. Outflow can be broken down into *evacuation* (aspiration), which is the flow out of the eye through the handpiece, and *incisional flow*, which is lost through the wound (Figure 2-22).

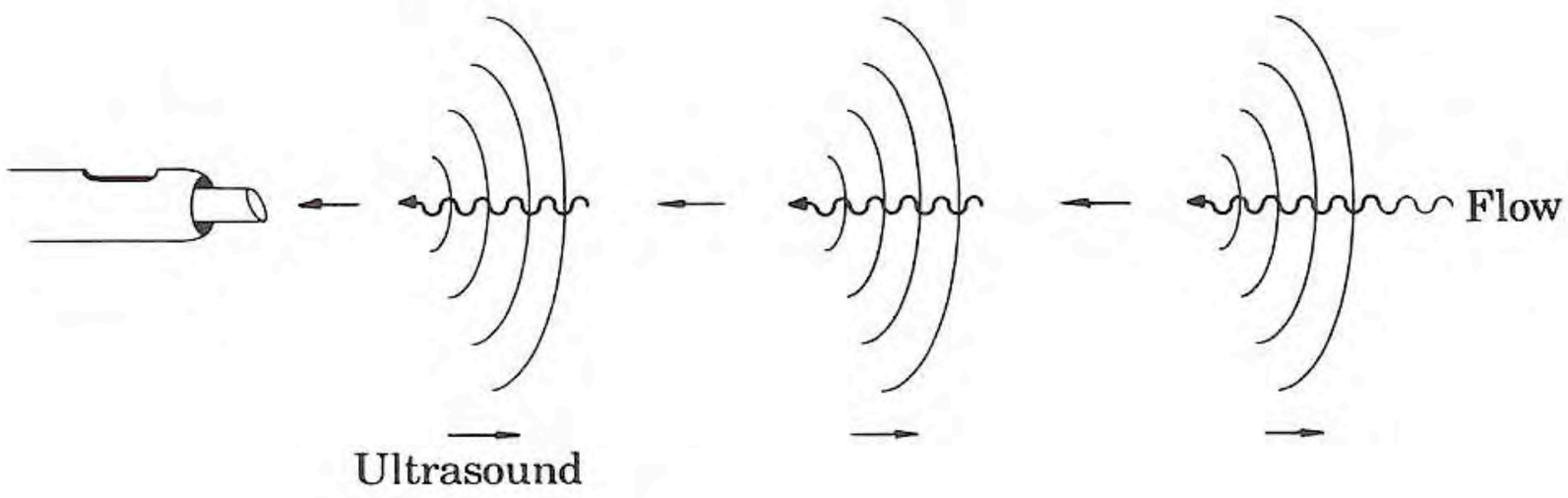


Figure 2-21. Pulser power.

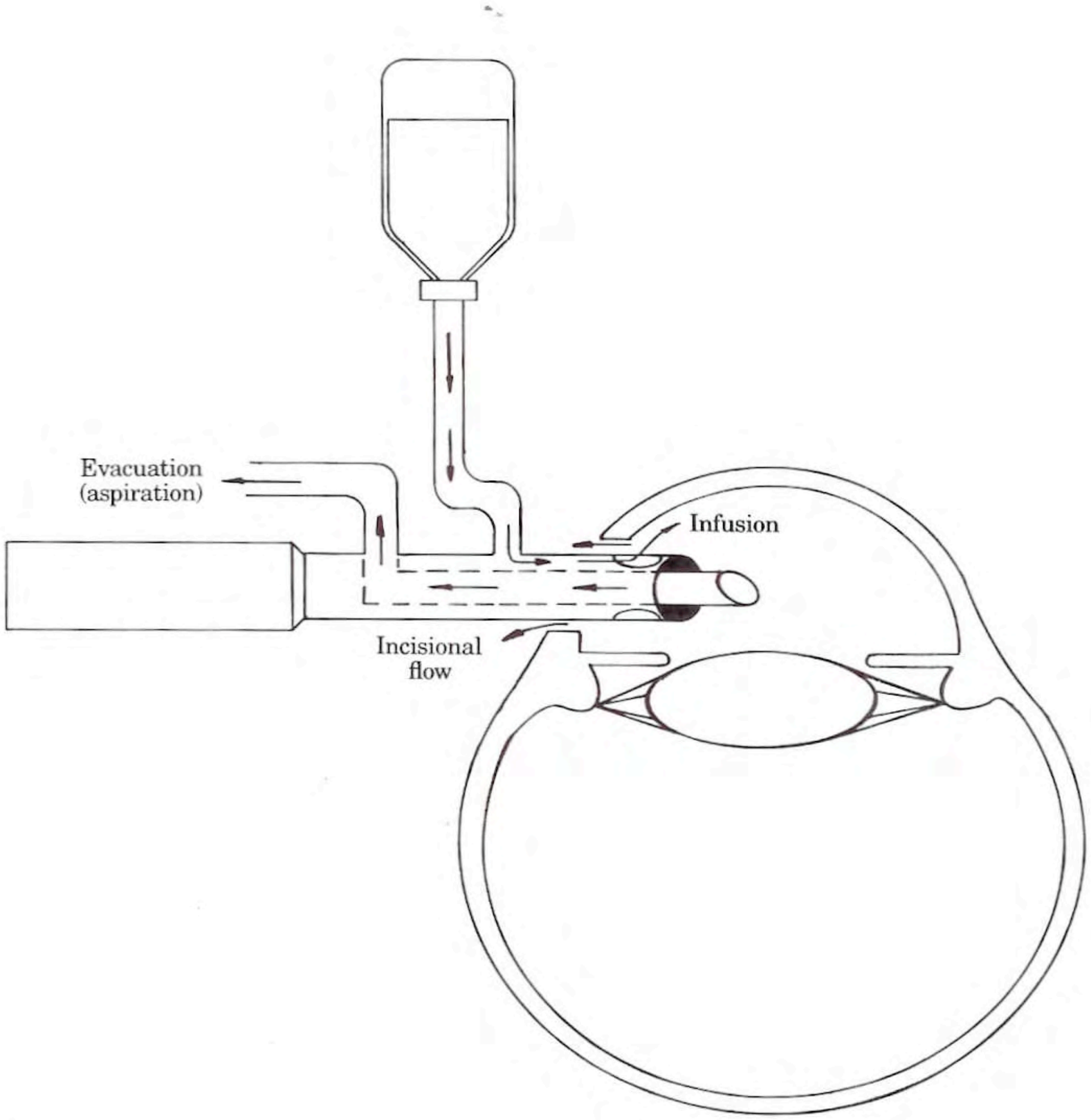


Figure 2-22. Components of flow.

Infusion flow depends on the bottle height and the resistance of the particular tubing and handpiece used. This must always be equal to or greater than the total outflow or the eye would collapse. If, for example, at a given bottle height a given handpiece is capable of 25 cc/min infusion and we set our evacuation flow at 25 cc/min, any additional loss such as leakage through the incision would result in some degree of collapse.

Since most modern equipment allows us to adjust evacuation (aspiration) rates to over 40 cc/min, it is important to have a clear understanding of a particular machine's infusion capabilities. A sales representative or owner's manual will certainly offer guidelines, but a surgeon can easily verify the exact flow characteristics of his own machine.

CALIBRATION OF FLOW

After proper equipment setup, simply time 1-minute infusion into a calibrated beaker for the low-, middle-, and high-bottle positions. Repeat this for each handpiece used. This then gives the infusion potential for each bottle height with each handpiece. Then immerse the tip into a beaker of water and time one minute of evacuation (aspira-

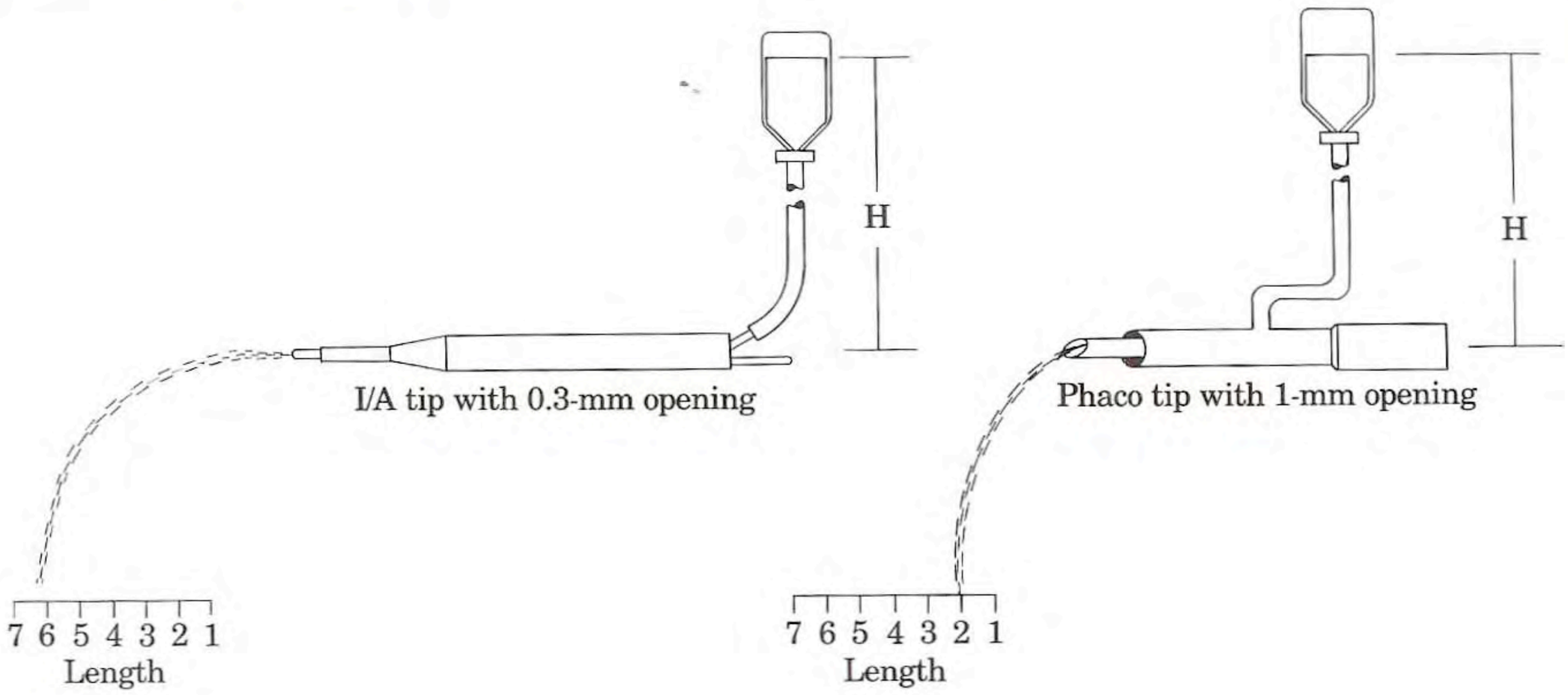


Figure 2-23

tion) into a calibrated collection container. If a machine offers flow settings in cc/min, check the measurement for 10, 20, and 30 cc/min and you will have verified its accuracy. For machines with a different type of calibration you should note, for example, that a 25 percent setting is equivalent to a certain measured rate in cubic centimeters per minute. Then for all future machine settings, be sure that potential infusion (bottle height) for the chosen handpiece is always greater than outflow. Two comments are appropriate at this point.

BOTTLE HEIGHT AND FLOW

First, one might deduce from this that simply running the bottles at maximum height all the time would be safest, since it provides the maximum infusion potential. This, however, fails to consider bottle heights' effect on intraocular pressure and surge potential and its effect on the force of the infusion stream with different size infusion ports. While the force of this stream is relatively small through the large ports, on most phaco tips it can be quite substantial through smaller openings on Mini I/A tips or capsule polishers and by itself represents a threat if directed toward corneal endothelium (Figure 2-23).

Second, in adjusting the infusion potential (bottle height) to greater than outflow, remember to take into account incisional loss. If a rigid infusion sleeve is available, a tight incision may be used and loss will be negligible. If, on the other hand, either by accident or design you are faced with a large amount of incisional fluid loss, raise the bottles to compensate.

EFFECTS OF FLOW

Having described the components of flow, let us now examine its effects. On the positive side, flow provides the force to move lens material to our instruments. When a piece of nucleus does not seem to be properly drawn toward the tip or if a wisp of 12 o'clock cortex seems beyond our reach, increasing the flow rate will brighten the day. On the down side, however, everything else will feel the urge to move towards the tip as well. If, for example, we need to remove cortex in the presence of a torn capsule, the flow should be reduced to avoid damaging the vitreous face. The aspiration port will then need to be maneuvered into more direct contact with the cortex to achieve occlusion. Remember that with peristaltic pumps, flow is controlled independently from suction. Suction settings are simply limits and only become relevant when a mass totally occludes the aspiration port. With diaphragm pumps, however, increasing the suction level with the foot pedal automatically increases the flow rate, and the surgeon must remember to reduce suction in situations where low flow is desirable such as with a torn capsule.

With peristaltic pumps there is a second effect of flow rate that is perhaps less obvious. When a tip is totally occluded the flow rate is zero, but the rate at which it is set will directly affect how fast the suction level rises. This effect is easily demon-

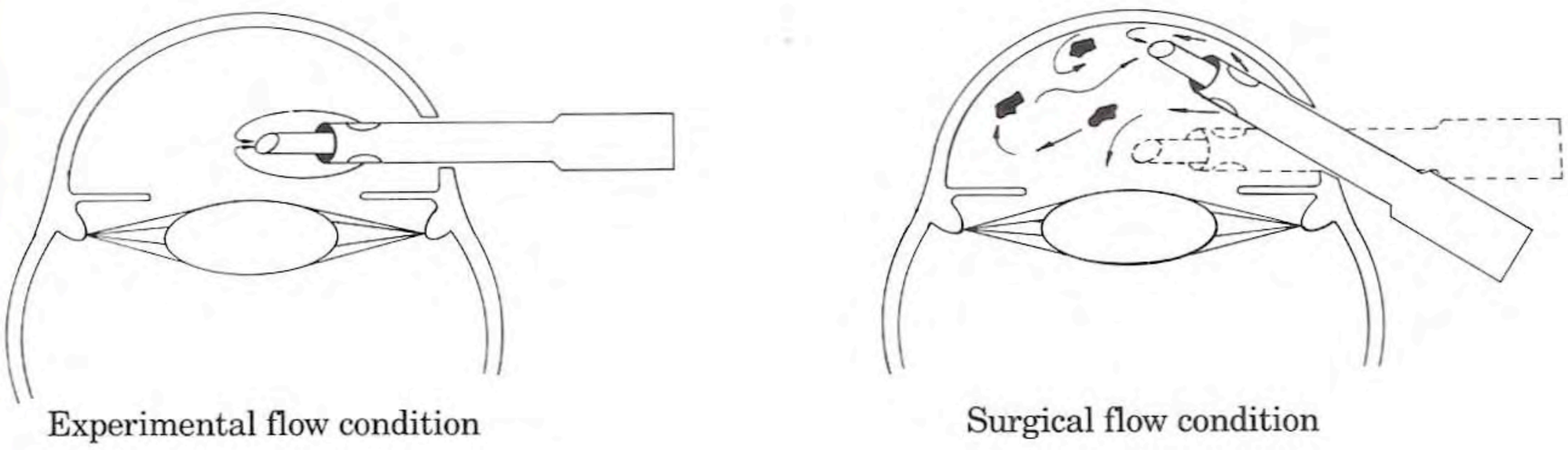
strated by occluding an I/A tip with your finger and varying the evacuation rate (aspiration), while observing the speed of the pump and the readout of actual suction level (if available). The higher the flow setting, the faster suction builds up. In the example of a torn capsule, the lower flow rate not only decreases the tendency to draw vitreous into the tip (and decrease turbulence) but also decreases the rate of suction rise when the tip is occluded. This allows a gentler, more deliberate stripping of cortex without any surge to further extend the tear.

Early studies on the effects of flow and the corneal endothelium were somewhat conflicting. Binder[5] concluded that "the irrigation procedure alone is deleterious to the cat endothelium," while Pollack and Sugar[3] stated that irrigation of the anterior chamber for 10 min caused no cell damage in rabbits. Neither study took into account the effect of flow rate when small particulate matter is present in the anterior chamber, nor did they simulate the effects of a moving phaco tip where flow patterns, proximity to cornea, and direction of streaming are constantly changing (Figure 2-24). In terms of modern technique, the persistence of viscoelastic protection to the cornea during emulsification may also be flow dependent.

From a clinical perspective, many surgeons now feel that reduced flow and turbulence are protective to the endothelium. The "dry extracapsular technique"[6] and current endocapsular phaco techniques bear testimony to this precept. It seems rational, therefore, to use as little flow as will efficiently perform the task at hand. When sculpting in the posterior chamber, for example, nucleus starts out already in contact with the tip, and very little flow is needed to carry particles into the evacuation port.

The author routinely uses 8 cc/min (peristaltic pump) for this part of the procedure and feels this provides great predictability for endocapsular maneuvers even when very close to the capsule. The astute reader may recall that in discussing power it was stated that high ultrasonic energy settings can effectively counter 12 cc/min of evacuation flow. There is, however, no contradiction here. First, the author's power setting is usually 40 percent and never more than 60 percent. Second, as the tip is engaged in sculpting, the nucleus mass partially occludes the tip, resulting in a smaller effective port diameter. Since a constant flow-rate type of machine is used to maintain 8 cc/min through the tubing, the effective flow velocity at the partially occluded port is actually greater than exists in a nonoccluded port. This is because to obtain the same flow per minute through a smaller opening, the velocity through the opening must be greater. In any case, a relatively low flow is recommended for sculpting; any limits on how low you can go should be checked with the manufacturer.

One possible concern here might be the effect of low flow on tip temperature. Depending on a particular machine's cooling design and power efficiency, avoidance of thermal buildup in the tip may require a certain minimal flow rate. This brings up another important point: If during phaco the flow is stopped because of occlusion in the evacuation line, the tip temperature can quickly



Experimental flow condition

Surgical flow condition

Figure 2-24

reach dangerous levels,[7,8] causing damage to the wound and corneal endothelium. Machines with audible feedback can indicate that pressure limits are reached with some type of beeping sound. This also indicates that evacuation flow is zero and should alert the surgeon to possible thermal danger. While a short burst of ultrasonics can be safely tried to clear the line, any prolonged power must be avoided. The tip should be removed from the eye and purged before surgery is continued. Machines without this type of feedback may require large leaky wounds to ensure a constant minimum flow by incisional loss. This, however, creates other problems as already discussed.

During later stages of the phaco procedure, when material needs to be drawn towards the tip, higher flow rates are needed. Usually 20 to 25 cc/min are effective, though the preferred level will obviously depend on the particular machine and surgeon.

Cortical cleanup is usually carried out at lower flow rates for several reasons. First, it is usually possible to apply the tip directly to the anterior cortical fibers, and high flow is therefore unnecessary to move material to the port. Controlled stripping from front to back results in a much cleaner capsule. Second, I/A tips usually have 0.2- to 0.3-mm ports as compared to approximately 1-mm openings for phaco instruments. As a result, for a given flow rate the velocity of fluid through the port is greater, and adjacent cortex is effectively drawn in. Commonly used rates vary between 4 and 25 cc/min depending on the manufacturer. Using the higher rates makes suction feel more responsive but requires higher vacuum levels in the tip and results in an increased tendency for fluid surge and collapse. There is also a greater risk of inadvertently capturing iris or capsule and, were this to happen, the suction level would increase more rapidly. The surgeon then has less time to react to correct the situation.

Removal of viscoelastic material is often accomplished with an I/A or Mini I/A tip. If Healon® is used, typical settings for cortical cleanup are efficient (for example, 4 cc/min and 300 mm Hg). Viscoat,® however, tends to require higher flow rates (for example, 12 cc/min) and suction pressures (for example, −400 mm Hg) to accomplish the task with the same expedience. Since Mini I/A tips have smaller infusion ports, be sure the bottle height (infusion potential) is adequate when using these higher flow settings.

SUCTION

As we have already seen, there is a critical difference in the way various pumps operate relative to vacuum levels. Peristaltic pumps produce a relatively gradual rise in pressure when the aspiration port is occluded, and the pressure drops again when the port is cleared. These pressure "adjustments" are made automatically by the machine, and the surgeon's only control is to set a limit on how high vacuum can go. With a diaphragm-type pump the vacuum level can be changed much more rapidly and is controlled by the surgeon's foot pedal. If a higher vacuum is used to aspirate lens material, this level will persist even after the port is cleared, unless the pedal is returned to its former position. With diaphragm pumps, the flow rate always fluctuates up and down with the vacuum level, while a peri-

TABLE 2-2. CONTRIBUTORS' MACHINE SETTINGS

SURGEON	DEVINE	FREEMAN	GIMBEL	HIRSCHMAN
Phaco Unit	Surgical Design Ocusystem II	Surgical Design Ocusystem II	Cavitron/Kelman 8000	Surgical Design Ocusystem II
Phaco Settings:				
Power (average)	40%	70%	50%	50%
Flow rate, cc/min (sculpting)	8	14	N/A	12
Suction level, mm Hg (sculpting)	150	100	N/A	70
Infusion sleeve	Solid	Solid	Flexible	Solid
I/A Settings:				
Flow rate, cc/min	4	12	N/A	8
Suction level, mm Hg	350	400	N/A	400
I/A port diameter, mm	0.3 & 0.2	0.3	0.3	0.3

staltic machine can be designed to more closely maintain a constant flow regardless of pressure changes. So which is better?

As with most things, there are advantages and disadvantages to both. A peristaltic machine can provide a constant flow rate (not all do) and therefore a constant intraocular pressure with a more stable intraocular environment. A diaphragm system can feel more responsive when rapid aspiration is desirable. Since flow rates are low, when diaphragm vacuum levels are low, there may be less total fluid use during the procedure. This is because peristaltic machines require higher flow settings to provide comparable vacuum level responsiveness. On the other hand, many surgeons prefer the control offered by a peristaltic machine's more gradual pressure buildup and therefore use low flow settings. The total fluid use then is comparable between pumps.

For the peristaltic user who wants vacuum responsiveness without high flow rate, an alternative exists in terms of technique. If, for example, during cortical cleanup, the tip is maneuvered to maintain material in the aspiration port, the vacuum level will not fall to baseline level, and you achieve "responsiveness" without need for high flow. In addition, the cortex that is being aspirated tends to pull out adjacent cortex, so as the tip is maneuvered to maintain occlusion, entire "sheets" are removed. This avoids leaving small wisps that may be difficult to aspirate, especially at the 12 o'clock position.

Most machines offer some type of suction level limit that can be set by the surgeon. This does not in any way control suction but simply acts as a governor to prevent suction from reaching unsafe levels. What constitutes a safe level will in large part depend on the individual surgeon, but certain design features should be considered.

The main concern is to prevent unacceptable surges of fluid (see Surge Prevention in Chapter 2) that would cause anterior chamber collapse and endanger capsule, iris, and cornea. The potential for surge increases with increased port diameter, intraocular pressure (bottle height), and vacuum levels. The larger phaco port will therefore require lower vacuum levels than the smaller I/A tip. Most manufacturers recommend or preset phaco vacuum levels in the −40 to −75 mm Hg range. A machine with surge prevention, however, is generally felt to be safe using −150 to −200 mm Hg during phaco. This improves cutting efficiency, allows aspiration of softer nuclear fragments and shell, and facilitates certain surgical maneuvers such as lollipoping or carouseling the nucleus.

HOW DO YOU REALLY SET THE DIALS?

For the reader who has resisted the temptation of skipping ahead to this part, the previous sections should make it clear that there are no "correct" settings even for a single machine. It is the surgeon's responsibility to understand the principles that will guide him when adjustments need to be made. No two operations or surgeons are exactly the same, and knowing when to turn things a little bit up or down makes our equipment safer, more useful, and more fun. Table 2-2 is therefore offered as only a general guideline showing what settings different contributors use with various machines.

KELMAN	KRATZ	NEUHANN	NORDAN	OSHER	SHEPHERD	SINSKEY
Alcon	Cavitron or Site	Surgical Design Ocusystem II	Cooper Vision Master or OMS Diplomate	United Surgical	OMS System II or Coopervision/Cavitron 9001	Coopervision or Site
70%	50%	50%	50%	50%	40%	50%
25	30	20	25	N/A	N/A	15
47	65	100	47	N/A	40	47
Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible
27	30	20	25	N/A	N/A	30
400	400	500	400	N/A	250	400
0.5	0.3	0.2	0.3	0.3	0.3	0.3

PHACO TIPS

The original phaco tips were 90 degrees and utilized soft silicone infusion sleeves. Beveling allows visualization of the posterior lip of the tip even when it is angled posteriorly. Its "point" allows for greater utility in maneuvering the nucleus and also concentrates its impact on a smaller area at the end of each stroke. It therefore improves penetration and cutting efficiency. On the downside, it is more difficult to occlude and its greater cross-sectional area reduces outflow velocity at the vicinity of the tip. The greater surface area of its edge and its larger projection of ultrasonic energy further interfere with evacuation flow. A component of the energy vector is directed perpendicular to the bevel and therefore more anteriorly towards the cornea when working above the iris plane.

In an effort to take advantage of a bevel and minimize its disadvantages, step tips are available, but the standard 30-degree bevel probably remains the most popular. While silicone infusion sleeves remain in wide use, rigid sleeves made of Teflon or metal offer distinct advantages and are available from some manufacturers.

The only criticism of the solid sleeve is decreased maneuverability within the eye. This opinion generally comes from using a very tight incision (2.85 mm), which limits the surgeon's ability to slide the sleeve in and out of the wound. Using a slightly larger incision (3.0 mm) allows for good maneuverability and results in a negligible loss of fluid through the wound.

REFERENCES

1. Barbell A: Health devices: Phacoemulsification systems. *ECRI* 1989;18:392.

2. Ito K: Experimental studies on clinical and pathological changes of neighboring tissues of lens by ultrasonic vibrating tip for phacoemulsification. *Japonica* 1970;74:725.

3. Pollack FM, Sugar A: The phacoemulsification procedure. II. Corneal endothelial changes. *Invest Ophthal* 1976;15:458–469.

4. Arentsen JJ et al.: Corneal opacification occurring after phacoemulsification and phacofragmentation. *Amer J Ophthal* 1977;83:794–804.

5. Binder P: Corneal endothelial damage associated with phaco emulsification. *Amer J Ophthal* 1976;82:48–54.

6. Anis AY: Illustrated step-by-step description of the Anis dry extracapsular cataract extraction techniques with in-the-bag lens implantation. *Seminars Ophthal* 1986;1:113–129.

7. Benolken RM, Emery JM, Landis DJ: Temperature profiles in the anterior chamber during phacoemulsification. *Invest Ophthal* 1974; 13:71–74.

8. Barbell A: Health devices: Phacoemulsification systems. *ECRI* 1989;18:379.