update/review

The physics of phaco: A review

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Despite its unparalleled success in the field of surgery, the precise mechanism of ultrasonic phacoemulsification cataract extraction remains controversial. We review the relevant peer-reviewed literature on the subject of power generation and tip–tissue interactions to clarify the current status of our knowledge. We conclude that phacoemulsification most likely operates by a combination of mechanisms, including direct action of the vibrating tip against tissue and indirect cavitational effects. Surgeons will benefit from understanding the physical principles underlying phacoemulsification because they will be better able to evaluate the performance of various parameters and different machine settings.

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United States patent 3 589 363, filed July 25, 1967, lists Anton Banko and Charles D. Kelman as inventors of "an instrument for breaking apart and removal of unwanted material, especially suitable for surgical operations such (as) cataract removal, including a handheld instrument having an operative tip vibrating at a frequency in the ultrasonic range with an amplitude controllable up to several thousandths of an inch."[1] Now, 37 years later, the fundamental mechanisms by which the system known as phacoemulsification operates remain controversial. While some authors describe the surgical advantages of a unique type of cavitational energy, others deny any role for cavitational energy in phacoemulsification (C. Guttman, MD, et al., "Microbursts of Ultrasound Increase Safety, Efficiency," Ophthalmology Times, April 15, 2003, pages 62–64).[2,3] Although definitive answers may prove elusive, it behooves surgeons to understand the language of physics and engineering, not only to analytically evaluate marketing claims but also to "promote the performance of a surgical procedure that is more gentle and efficient, thus improving outcomes and minimizing complications."[3]

Basic Principles of Power Generation

The prerequisite for the removal of a cataract through a small incision is a technique to break up the hard nucleus into emulsate for aspiration. Inspired by the dentistry technique to remove tarter with a metal tip that oscillates longitudinally at frequencies in the ultrasonic range, Kelman ingeniously adopted this principle and combined the oscillating tip and the evacuation tube into a hollow needle.[1] A special titanium alloy is the material of choice for such applications because of a favorable strength-to-weight ratio as well as biocompatibility and resistance to fragmentation.

The phaco handpiece incorporates a transducer for converting high-frequency, alternating current into mechanical vibrations. Magnetostrictive transducers are based on packs of ferromagnetic lamellae, surrounded

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by an electric coil. The magnetic field induced by the high-frequency electric current flowing through the coil excites the oscillation. The advantages of magnetostrictive transducers include contact-free excitation, which prevents deterioration at the junction of the current and the transducer. These transducers, coupling elements, and the entire handpiece are rugged, withstanding mechanical injury, and have a long lifespan. Their primary disadvantage is a relative low grade of efficiency. Only a small part of the energy input is transformed into mechanical action; most becomes heat. Heating not only carries the risk for tissue burn but also makes the transducer lose efficiency with rising temperatures. Also, in the original design, the concentric aspiration line had to be brought out in front of the lamellar stack, necessitating 2 sharp bends that frequently clogged.

Recent improvements include increased efficiency through sophisticated ferromagnetic metal alloys with rare earth elements and engineering modifications that allow the irrigation and aspiration lines to be concentrically brought straight through the track to the tip. This not only avoids the clog-prone bends but also provides a double stream of constantly flowing cooling fluid through all elements of the vibrating system, obviating the need for a separate cooling system, as found on the older handpiece.

Piezoelectric transducers are based on the reversals of the piezoelectric phenomenon. Upon compression, certain crystals produce electric current. In reverse, electric current causes the crystal to contract. Applying current to a crystal at high frequency will cause it to oscillate at that frequency.

The crystal is mounted on the ultrasonic horn, a piece of tubing of narrowing diameter, eventually ending with the attachment of the phaco needle. The narrowing diameter tube acts as an amplifier to generate adequate power for emulsification.

The advantages of piezoelectric crystals include a high grade of efficiency and therefore little inherent heat generation, with no need for extra cooling. The crystals' low mass allows rapid movement and precise control. Many new handpieces use multiple crystals (usually 2 to 4 sets) to maximize responsiveness and provide adequate power to emulsify the mature hard nucleus. Disadvantages include the connection points between crystal and electric current, the connections among the multiple layers of crystals that are needed to provide adequate stroke amplitudes, and the structural brittleness of the crystal itself. These properties limit the longevity of the transducers. They are delicate and deteriorate from accidental mechanical injury and the oscillation they produce.

Every material has an inherent frequency at which it vibrates naturally. This is called its *resonant frequency.* If excited to vibrate at this frequency, the transformation into mechanical amplitude will be optimal and the creation of other forms of energy, principally heat, will be minimized. The creation of balanced crystals, their attachment to the horn, and the weight of the titanium phaco needle must therefore be carefully controlled during manufacturing.

The phaco procedure is less controlled. In the course of phaco, the needle is passed through and inside material of inconsistent resistance. The aqueous is less resistant than a soft nucleus, and a soft nucleus less resistant than a mature one. Thus, for example, as the phaco needle travels through balanced salt solution into a hard nucleus, the resonant frequency must be adjusted to prevent inefficient emulsification. The result of inefficient emulsification is prolonged phaco time, higher power, and increased heat generation. Therefore, modern phaco systems now have a built-in feedback loop that constantly adjusts or tunes the oscillating frequency to an optimal resonance. This is a function of the central processing unit (CPU) of the machine. It will read the change in resistance of the phaco needle and make minute adjustments in the stroke length or frequency. The greater the frequency of the corrections, the more effective the emulsification will be.

Power is the product of oscillatory frequency (hertz, cycles per second, sec^{-1}) and the work associated with a given stroke length. Frequency is defined as the speed of the needle movement. It is determined by the manufacturer of the machine. Currently, most machines operate at a frequency of between 35 000 cycles per second (hertz) and 45 000 cycles per second. This frequency range is the most efficient for nuclear emulsification. Lower frequencies appear to be less efficient, and higher frequencies create excess heat.

Frequency is held constant by tuning circuitry designed into the machine's CPU. Stroke length is defined as the length of the needle movement. This length is generally 2 to 6 mil (thousandths of an inch).

Most machines operate in the 2 to 4 mil range. Longer stroke lengths are prone to generate excess heat. The longer the stroke length, the greater the physical impact on the nucleus. Stroke length is determined by foot pedal excursion in position 3 during linear control of phaco. Although the frequency is unchanged, the amplitude of the sine wave is increased in direct proportion to the depression of the foot pedal.[3]

Effects at the Phaco Tip

The action of phacoemulsification can include several mechanisms including direct mechanical cutting, termed the *jackhammer effect*, and implosion of microcavitation bubbles, producing extreme yet brief instances of heat and pressure.[4] Cavitation can be described simply as growth, oscillation, and collapse of micron-sized bubbles in liquids under the influence of an acoustic field. Cavitational effects may be created as the phaco needle moves through the liquid medium of the aqueous at ultrasonic speeds, creating intense zones of high and low pressure. Low pressure, created with backward movement of the tip, may pull dissolved gas out of solution or vaporize the aqueous solution itself, giving rise to microbubbles. Forward tip movement then creates an equally intense zone of high pressure. This produces compression of the microbubbles until they implode.

However, Boukhny[2] has stated that "all cutting occurs due to mechanical cutting, much like during jackhammer action…. cavitation plays no useful role in phaco or other cutting ultrasound applications." The jackhammer effect is the direct mechanical impact of the physical striking of the needle against the nucleus.[3] The efficiency of this mechanism depends on 2 main prerequisites:

1. Rapid forward acceleration of the phaco tip. This overcomes the inertia of the nucleus, penetrating it rather than driving it away.
2. Close mechanical contact between the tip and the nucleus. Engineers call this force *coupling*. It is obtained by pressing the tip against the nucleus or by pressing the nucleus to the tip.

Bond and Cimino[5] state that "the primary mechanism for tissue fragmentation is shown to be horn–tip impact and other mechanical forces, operating in combination with hydrodynamic forces applied to the tissue on the forward stroke in each cycle. No evidence of cavitation in tissue was observed." Using an ultrasonic unit similar to the CUSA (Valleylab) set at 23 kHz with peak amplitude of about 330 μm, they measured the transmitted waveform in water with calibrated hydrophones. While they observed both acoustic streaming and cavitation in water, they did not find evidence of cavitation in tissue interactions. They note that "the interaction of acoustic energy with tissue can be expected to be very different from the case of the interaction with water."[5] In water, they found a power threshold above which a pattern of stable cavitation bubbles developed. Using high-speed photography, they described a model of tip–tissue interaction for efficient fragmentation that relies on forward stroke mechanical force and suction. Bond and Cimino found a "loss of contact" with tissue during the back stroke, "which limits the fragmentation process to the forward (downward) stroke."[5] "Given the absence of the negative part of the pressure cycle, it does not appear that it is possible that cavitation can be a significant fragmentation mechanism for the conditions of 'good fragementation.'"[5]

A more recent study investigated the specific issues of the mechanisms of phacoemulsification with a commercially available unit, using straight, 45-degree beveled tips in both continuous and pulse modes (L.J. Bond, et al., "Physics of Phacoemulsification," presented at the 5th World Congress on Ultrasonics, Paris, France, September 2003). Various ultrasonic measurements were made with 3 types of samples: hard and soft tissue phantoms and fresh porcine eyes. A hydrophone wide-band receiver with effective bandwidth from 10 kHz to 2.25 MHz was used to record the ultrasonic signals. The ultrasonic waves produced by the tip (horn)–sample impact (at 40 kHz) and any acoustic emissions propagated through the test sample to the receiver were measured in the configuration (Figure 1). The unit was operated with all types of samples with and without irrigation and suction. In all cases, material was fragmented and no significant cavitation was detected. Both time domain and spectral measurements were made, and no evidence of transient cavitation was recorded. Under some conditions, very low level cavitation events were recorded (Figure 2).

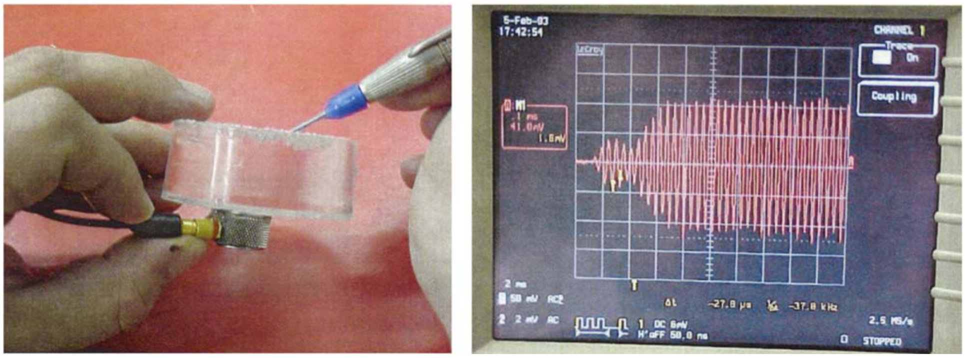

Figure 1. *Left*: Phacoemulsification tip, sample, and wideband receiver. *Right*: Example of transmitted 40 kHz pulse.

Bond also conducted measurements to determine the source of the "cavitational hiss" heard during phacoemulsification. He noted that without irrigation, no hiss was audible. The unit was then operated with irrigation and no sleeve. The shoulder at the top of the tip was noted to be the source of a fine atomized mist (Figure 3). Bond reported that the hiss only occurred when the shoulder of the horn was immersed in fluid or the sleeve, which entrains irrigation, was attached. Further investigation showed that some low level cavitation events occurred near the tip when the irrigation fluid had transported microbubbles down the sleeve. Bond therefore concluded that the cavitational hiss was produced at the shoulder of the tip and was not relevant to tissue interaction. Based on these findings, it is reasonable to conclude that ultrasonic cavitation occurs in fluid but not during tip–tissue interaction per se.

Ensminger,[6] however, has noted that "many of the useful effects of ultrasonic energy are associated with cavitation, a term used to describe the formation of cavities, or bubbles, in a liquid medium." He distinguishes gaseous cavitation, a low intensity release of dissolved gas, from vaporous cavitation, a high intensity vaporization of the liquid medium. Vaporous cavitation is associated with very high pressure and temperature, up to 10 000 atmospheres and 3000 °C.[7] "At the same time, free chemical radicals are produced, and even very tough metals are eroded."[7]

Pacifico notes that "most surgeons view phacoemulsification as a single energy that emulsifies the cataractous lens with an action similar to that of a miniature jackhammer, ignoring the possibility that the procedure's ultrasound energy may have other dimensions and uses in ophthalmology."[8] By "other dimensions," Pacifico means cavitation. He schematically describes the creation of a cavity in lens material by means of energy release secondary to bubble implosion: "[P]erhaps the cavitation effect is most easily visible when the phaco cuts clearly go deeper and beyond where mechanical cutting would have stopped."[8] Davis echoes

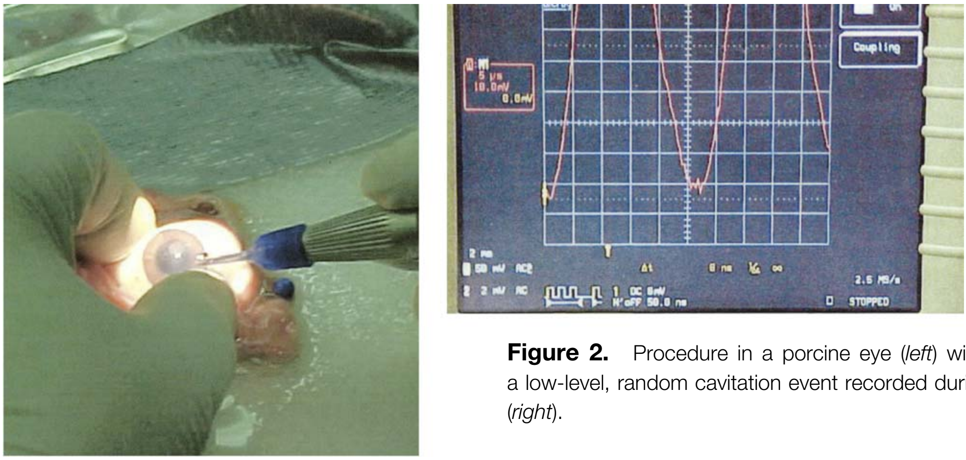

Figure 2. Procedure in a porcine eye (*left*) with an example of a low-level, random cavitation event recorded during the procedure (*right*).

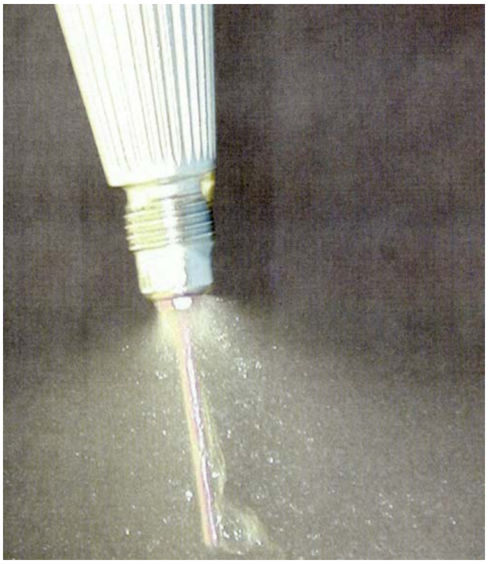

Figure 3. Atomization of irrigation fluid at tip (horn) shoulder.

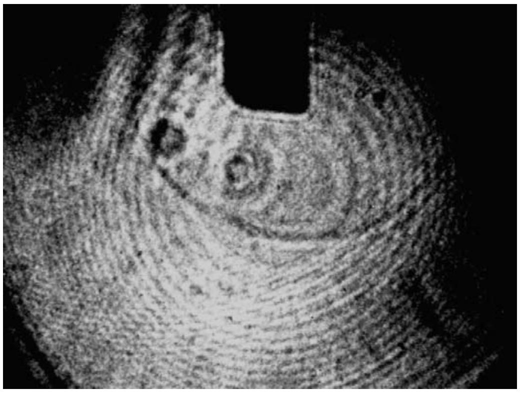

Figure 4. Ultrasonic tip in water bath showing wave propagation and presence of presumed cavitation bubbles.

this observation: "Phaco surgeons often notice cataract tissue breakdown anterior to their phaco needles without the tip touching the cataract. This is because the shock waves are focused in front of the phaco needle as shown by Schlieren imaging."[9] He cites Fishkind's video presentation of shock waves in vitro to support this concept (W.J. Fishkind, MD, "Pop Goes the Micro Bubbles," video presented at the ASCRS Symposium on Cataract, IOL and Refractive Surgery, Seattle, Washington, USA, June 1996).

Schafer reported an in vitro assessment of cavitation generation and cavitational effects associated with phacoemulsification, specifically contrasting micropulse applications of ultrasound (US) with continuous power (M.E. Schafer, MD, "Cavitation Generation and Cavitational Effects in Phacoemulsification," presented at the ASCRS Symposium on Cataract, IOL and Refractive Surgery, San Francisco, California, USA, April 2003). By taking acoustic measurements from an ultrasonic tip immersed in a water tank, Schafer demonstrates the production of cavitational effects (Figure 4). He also suggests that micropulses of US give rise to a phenomenon known as transient, as opposed to stable, cavitation. Stable cavitation involves volume oscillations of gas bubbles in a continuous sound field, while the more violent transient cavitation is associated with collapse of the gas bubbles during a single US cycle or after a small number of cycles.[10] In the final phase of collapse, pressure and temperature inside the bubble can reach thousands of millimeters of mercury and Celsius degrees. These high temperatures lead to the emission of light (sonoluminescence) and can cause bond dissociation in molecules, producing free radicals able to react with biomedical species in the same way as those produced by ionizing radiation.[11] Immediately after the bubble rebound, the high-pressure shock wave emanates from the bubble location and causes mechanical damage to the surrounding fluid.[12] Hence, the greatest destruction of tissue by ultrasonic cavitational energy is mediated by violently collapsing bubbles.

Several authors cite the formation of free radicals as evidence of cavitation during phacoemulsification. These species are thought to be generated when the heat from the implosion of cavitation bubbles causes the decomposition of water.[13–15] Holst et al.[16] used a single photon counting apparatus and luminol in rabbit eyes to demonstrate chemoluminescence secondary to the production of free radicals during phacoemulsification. They also obtained data correlating the amount of free radicals produced with the amount of ultrasonic power used. Topaz et al.[17] demonstrated sonoluminescence under simulated phacoemulsification in aqueous medium using electron paramagnetic resonance spectroscopy and photon detection. They also noted modification of acoustic cavitation and elimination of sonoluminescence by saturation of the solution with carbon dioxide. The release of cavitational energy during phacoemulsification has also been confirmed in vitro by experiments performed by Reinhert Teizel at the Physikalisches Institut, University of Erlangen, Germany (personal communication, William J. Fishkind, MD, December 3, 2003). Using laser photography techniques, the cavitation wave was photographed at 2 to 5 nanosecond intervals (Figure 5).

Taken as a whole, the experimental evidence suggests the interplay of mechanical and cavitational forces operating at the phaco tip. While mechanical forces emulsify tissue directly on contact with each forward stroke of the phaco tip, the activation and implosion of cavitation bubbles in the aqueous environment of the anterior chamber may also disrupt lens material. Transient cavitation will, however, only occur above a certain threshold of US power. For example, the American Institute of Ultrasound in Medicine has accepted the mechanical index (MI), which is a dimensionless quantity proportional to the US rarefaction pressure and inversely proportional to the square root of the frequency of the US wave, as a predictor of possible biological responses to transient cavitation.[18] Although more generally related to safety parameters for diagnostic US, an MI less than 0.7 indicates a low probability for transient cavitation effects.[19] This theoretical prediction may be incorrect if the medium through which the ultrasonic waves pass behaves as a viscoelastic fluid. Based on the fact that MI depends directly on elasticity, Allen and Roy[20] have reformulated the MI criteria. This reformulation may have implications for the intraocular environment in which viscoelastic substances have been specifically introduced for the protection of tissues.

Current Research Directions

Ironically, as controversy over the mechanism of US continues to swirl and bubble, reduction in the use of US energy itself as an extractive modality in cataract surgery has become a primary surgical goal. Innovations in fluid management including low-compliance tubing and cassettes, microprocessor control of pumps, aspiration-bypass and flow-restriction systems, high-resistance down-sized phaco tips, modification of parameters during tip occlusion, and irrigation pressurization have allowed safe use of high flow rates and very high vacuum levels, permitting extraction of moderately dense cataracts with minimal to no use of US.[21–23] Evidence is continuing to mount that the reduction in US use correlates with faster visual rehabilitation and improved outcomes.[24]

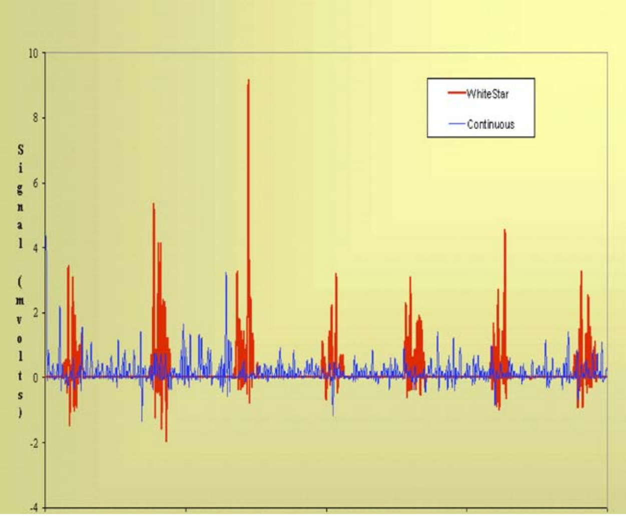

Figure 5. Transient cavitation during micropulse phacoemulsification.

The advent of bimanual microincision phaco, which uses power modulations such as micropulse technology to minimize US power, has eclipsed the early promise of laser phaco systems to deliver non-thermal cataract extraction (A. Franchini, MD, “From Laser Phaco to Cold Ultrasound: 10 Years of Microinsision Cataract Surgery,” presented at the ASCRS Symposium on Cataract, IOL and Refractive Surgery, San Diego, California, USA, May 2004).[25] Micropulse technology may not only reduce US use but also have fluidic advantages, as Steinert and Schafer demonstrated with high-resolution, color, digital US imaging (R.F. Steinert, MD, M.E. Schafer, MD, “Thermal Energy and Turbulence with WhiteStar and Conventional Phacoemulsification,” presented at the ASCRS Symposium on Cataract, IOL and Refractive Surgery, San Francisco, California, USA, June 2003). They showed that micropulse power modulation decreases fluid turbulence around the phaco tip and thereby improves followability (Figure 6).

Other alternative extractive technologies, such as pulsed warm water, may ultimately find wider acceptance.[26] As patients come to cataract surgery earlier in the course of their disease[21] or opt for refractive lens exchange before the development of visually significant cataract,[27] minimization of surgical morbidity and rapid achievement of excellent uncorrected visual acuity have become more important goals (R.H. Osher, MD, “Early Uncorrected Vision: An Important

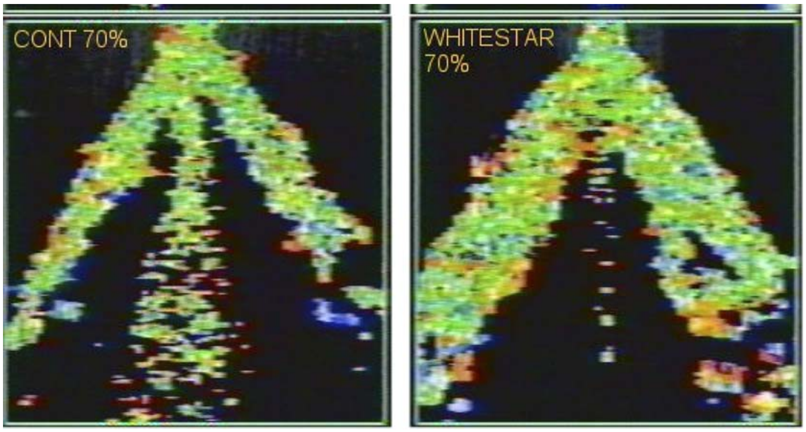

Figure 6. Increased fluid velocity away from the tip with continuous mode (*left*) as opposed to micropulse (*right*) phaco suggests that continuous phaco is more likely to push nuclear fragments away from the tip.

Measurement in Contemporary Cataract Surgery,'' presented at the Royal Hawaiian Eye Meeting, Kauai, Hawaii, January 2004). Regardless of the specific direction cataract extraction moves, the trend toward reduction of US energy will certainly continue because of its demonstrated correlation with improved outcomes.[21]

In this regard, 1 challenge for surgeons, particularly those conducting research, has been the lack of objective comparative data among the phaco machines produced by the various manufacturers. Arbisser and Schafer recently reported their attempt to compare the ultrasonic energy levels of 2 different machines and concluded that ''the machine-provided data is extremely difficult to interpret and use for this purpose, and manufacturers should be encouraged to provide more meaningful data in a simpler format'' (L.B. Arbisser, MD, M.E. Schafer, MD, ''Quantitative Investigation of Ultrasonic Energy Levels Required During Cataract Surgery,'' presented at the ASCRS Symposium on Cataract, IOL and Refractive Surgery, San Francisco, California, USA, June 2004).

Conclusions

The evidence amassed thus far regarding the mechanism of ultrasonic phacoemulsification supports a direct tip–tissue interaction. Indirect evidence, primarily from in vitro studies, suggests a role for cavitational emulsification.

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