Phaco has turned 40, gracefully

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"Perhaps the most outstanding characteristic of this era of phaco is the unrelenting quest for excellence that continues to challenge the innovative spirit of cataract surgeons."

Phacoemulsification is the disassembly and removal of the crystalline lens. From its introduction in the late 1960s to the present, phaco has evolved into a highly effective method of cataract extraction. Incremental advances in surgical technique and the simultaneous redesign and modification of technology have led to increasing safety and efficiency. Among the advances that have shaped modern phaco are incision construction, continuous curvilinear capsulorhexis, cortical cleaving hydrodissection and hydrodelineation, and nucleofractis techniques. The refinement of cataract removal through a small incision has improved phaco and permitted rapid visual rehabilitation and excellent ocular structural stability. Perhaps the most outstanding characteristic of this era of phaco is the unrelenting quest for excellence that continues to challenge the innovative spirit of cataract surgeons.

US patent 3589363, filed on the 25th of July 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' [101]. Now, over 40 years later, the fundamental mechanisms by which the system known as phaco 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 phaco [1]. 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' [2].

"Although all phaco machines obey the same general principles, each model of machine is unique; therefore, the parameters do not transfer identically from machine to machine."

Phaco represents a complex interplay of various forms of energy with lens material. The mechanics of phaco depend on the relationships among ultrasonic energy, anterior chamber irrigation, flow rate and vacuum extraction of lens material. The phaco handpiece includes piezoelectric crystals that convert electrical energy into mechanical energy. The forms of energy used to break up the cataract include a jackhammer effect created as the needle physically impacts the nucleus [101], an acoustic wave traveling in front of the advancing needle [2], and cavitational energy, in which microbubbles are stripped out of solution [2]. Phaco power represents a combination of frequency and stroke length. The frequency is the speed of needle movement measured in cycles per second. In general, the preset frequency is between 27 and 54 kHz. The most efficient frequency for ultrasonic phaco is between 38 and 48 kHz. The frequency is preset by the machine manufacturer and is not usually under the surgeon's control. The stroke length represents the actual distance the phaco needle travels as it moves back and forth.

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The surgeon can control this value: through the use of a foot pedal; linear control of phaco power generally occurs in foot pedal position 3.

Phaco parameters represent a group of numbers that control the various functions of a phaco machine. The primary parameters are power, aspiration flow and vacuum pressure. In a peristaltic pump system, depression of the foot pedal to position 2 directly controls the rate at which the pinch roller rotates. Machines offer fixed rates of flow or linear control of flow, as well as alterations in the flow rate when the machine senses an occlusion (i.e., in the face of rising vacuum). In peristaltic systems no vacuum is present until the tip begins to become occluded and resistance to flow is sensed. Vacuum pressure rises as flow is reduced by material on the tip. At occlusion, aspiration flow ceases and the maximum vacuum is reached. The maximum vacuum level is set by the surgeon as one of the parameters of a peristaltic system, but in fact this setting specifies the vacuum level at which the pump stops. In a Venturi pump, (named after the Italian physicist Giovanni Battista Venturi) the foot pedal directly controls the application of vacuum; aspiration flow occurs in response to vacuum pressure. According to the classic Venturi principle, the flow of pressurized gas through a narrowed tube creates the vacuum. Unlike a peristaltic pump, where the vacuum does not exist until there is resistance to flow, with a Venturi pump, vacuum is always present. The surgeon sets the maximum vacuum level as one of the parameters and there is no setting for aspiration flow. The vacuum increases in a linear fashion as the foot pedal is depressed to foot position 2. Machines that feature a bidirectional foot pedal also allow control of vacuum with yaw, that is, movement of the foot pedal in a direction parallel (rather than perpendicular) to the floor. This feature permits greater flexibility in separately controlling the application of vacuum and ultrasound power. Although all phaco machines obey the same general principles, each model of machine is unique; therefore, the parameters do not transfer identically from machine to machine. Each surgeon should adjust to best effect, or optimize, his or her parameters for each machine they use. While surgical facility or ease of use and absence of complications represent intraoperative criteria for optimization, early postoperative outcomes best reflect the impact of phaco on the eye [3].

Modulations of phaco power have been developed to reduce the risk for thermal injury to tissues and to increase efficiency. The initial developments in this arena consisted of pulse mode and burst mode. In pulse mode, the power is modulated to turn on and off a certain number of times every second (described as pulses per second [pps]). There is linear control of power but a fixed interval between pulses. The use of pulse mode reduces phaco power delivery by 50% and maintains a more stable anterior chamber. It also allows a firmer grasp on lens material and reduces chatter at the tip because vacuum builds between each pulse. Burst mode is a power modulation that uses a fixed percentage of power, a programmable burst width (duration) and linear control of the interval between bursts.

More recently, the introduction of the programmable variable duty cycle and ultrasound pulse widths of less than 5 ms has increased control and efficiency. Improvement of clinical outcomes with these new technologies has been demonstrated [4]. The ability to vary control of the application of ultrasound power to within a period of several milliseconds has revolutionized phaco technology. The first generation of phaco machines only allowed application of continuous power at a fixed level. Following the development of linear power control, the first power modulations were developed – pulse and burst modes – as mentioned previously. The application of these modulations reduces the use of ultrasound energy and permits rapid visual rehabilitation after surgery: the reduction of effective phaco time correlates with improved uncorrected visual acuity at the first visit after surgery [5]. The introduction of millisecond-level control and variable duty cycle applications has permitted further reduction of ultrasound energy and eliminated the risk of thermal injury to the cornea, paving the way for the adoption of biaxial microincision cataract surgery [6].

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Surgeons should try a variety of power settings, including pulse and burst modes, variable duty cycles and percentage power ceilings in order to develop parameters best suited to their individual techniques. Machines now also feature standard longitudinal, torsional and elliptical tip motions that can be customized in amplitude to suit a variety of techniques. Intraoperative awareness and moment-to-moment assessment of surgical success offer the best opportunity to alter settings and improve results. The surgeon should recognize that insufficient holding implies a need for greater vacuum, whereas an uncomfortable amount of surge calls for a reduction in vacuum. Poor follow-ability may require increased aspiration flow or vacuum if the problem is bringing material to the tip or higher power if material comes to the tip but then bounces off when ultrasound is applied. A shallow chamber indicates a need to check the irrigation bottle height and the continuity and patency of the irrigation tubing from the bottle to the eye. Understanding the roles of flow, vacuum and power will allow the surgeon to make machine adjustments that vastly improve the surgical experience.

Perhaps the most critical aspect of intraoperative control during phaco is represented by chamber stability. Chamber stability describes the maintenance of volume in the working space of the aqueous environment, from the apex of the corneal endothelium to the central posterior capsule. The balance between irrigation and aspiration plus leakage determines this volume. Leakage can be minimized by proper incision construction. However, the aspiration flow rate of fluid exiting the eye can increase suddenly but predictably during surgery due to the phenomenon known as 'surge flow'. Surge flow describes the loss of aqueous volume in the working space of the anterior segment that can occur when material which has occluded the phaco tip is suddenly evacuated from the chamber. The surge occurs because the high vacuum reached during occlusion actually exerts its force throughout the aspiration tubing and creates a pinching or narrowing of the tubing. When the vacuum is released the pinched tubing expands and fluid rushes in to fill the void. Phaco machine innovations such as low compliance tubing and rigid cassettes minimize the elasticity in the system and reduce surge flow. Other designs intended to reduce surge include the aspiration bypass system (a small aperture on the side of the phaco tip that allows fluid flow into the handpiece despite an occlusion on the front of the tip) and in-line filters (a mesh designed to trap material upstream from a small aperture, which poses a size restriction to flow) [7].

The concept of follow-ability means the facility with which nuclear material flows towards, is held by, and evacuated through, the phaco tip. One antonym of follow-ability is chatter, which describes the situation when material repeatedly bounces off the phaco tip without following the aspiration flow up the tube. The metaphor of magnetism is sometimes used to describe the attraction of material towards the tip; while it is the aspirational flow that draws the material. In coaxial phaco (with the irrigation sleeve on the phaco tip) the irrigation stream tends to push material away so that aspiration must overcome irrigation for attraction to occur. In both coaxial and biaxial phaco, longitudinal ultrasonic vibration of the phaco tip also acts as a repulsive force that must be overcome by aspirational flow and, during occlusion, by vacuum pressure, to bring material and hold it on the tip as it is mobilized and emulsified. Alleviating the repulsive force of longitudinal tip motion has been the impetus behind the development of nonlongitudinal sonic and ultrasonic energy-delivery systems, such as oscillatory, torsional or elliptical tip motions. The balancing of these competing forces at the phaco tip underlies much of the logic of setting parameters for efficient surgery.

> “In both coaxial and biaxial phaco, longitudinal ultrasonic vibration of the phaco tip also acts as a repulsive force that must be overcome by aspirational flow...”

During development, various alternatives to ultrasound have been investigated but none has gained a significant number of users. These modalities include pulsed warm water jet technology, laser modalities (Er:YAG, Nd:YAG) and mechanical modalities (PhacoTmesis, Vortex Phacoemulsification) [8]. While safety and efficacy have been demonstrated for most of these systems, they remain limited by cataract density. Some of the advantages of these systems, for example, the absence of thermal energy in laser phaco, have been essentially obviated by the improved power modulation and tip motion control available now with ultrasound technology. Other potential advantages, such as reduction of posterior capsular opacification, have not been born out [9]. As improved surge control has allowed higher vacuum levels and increased the relative importance of aspiration compared with emulsification for lens extraction, the ability to occlude the tip and perform controlled mechanical disruption with modern chopping techniques and ultrasound energy has continued to prove its superiority.

Since the time of Charles Kelman's inspiration in the dentist's chair (while having his teeth ultrasonically cleaned), incremental advances in phaco technology have produced ever-increasing benefits for patients with cataract. The modern procedure simply was not possible even a few years ago and until recently, prolonged hospital stays were common after cataract surgery.

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The competitive business environment and the wealth of surgeons' ingenuity continue to demonstrate synergistic activity in the improvement of surgical technique and technology. Future advances in cataract surgery will continue to benefit our patients as we develop new phaco techniques and technology.

Financial & competing interests disclosure

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