

Fluid dynamics, cavitation, and tip-to-tissue interaction of longitudinal and torsional ultrasound modes during phacoemulsification

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PURPOSE: To describe the fluidic events that occur in a test chamber during phacoemulsification with longitudinal and torsional ultrasound (US) modalities.

SETTING: Pasteur Ophthalmic Clinic Phacodynamics Laboratory, Santiago, Chile, and Nanyang Technological University, Singapore.

DESIGN: Experimental study.

METHODS: Ultra-high-speed videos of a phacoemulsifying tip were recorded while the tip operated in longitudinal and torsional US modalities using variable US power. Two high-speed video cameras were used to record videos up to 625 000 frames per second. A high-intensity spotlight source was used for illumination to engage shadowgraphy techniques. Particle image velocimetry was used to evaluate fluidic patterns while a hyperbaric environmental system allowed the evaluation of cavitation effects. Tip-to-tissue interaction at high speed was evaluated using human cataract fragments.

RESULTS: Particle imaging velocimetry showed the following flow patterns for longitudinal and torsional modes at high US powers: forward-directed streaming with longitudinal mode and backward-directed streaming with torsional mode. The ultrasound power threshold for the appearance of cavitation was 60% for longitudinal mode and 80% for torsional mode. Cavitation was suppressed with pressure of 1.0 bar for longitudinal mode and 0.3 bar for torsional mode. Generation of previously unseen stable gaseous microbubbles was noted. Tip-to-tissue interaction analysis showed the presence of cavitation bubbles close to the site of fragmentation with no apparent effect on cutting.

CONCLUSIONS: High-speed imaging and particle image velocimetry yielded a better understanding and differentiated the fluidic pattern behavior between longitudinal and torsional US during phacoemulsification. These recordings also showed more detailed aspects of cavitation that clarified its role in lens material cutting for both modalities.

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 Online Video

Since the introduction of phacoemulsification by Kelman in 1967,¹ phacoemulsification systems have evolved, with technological advancements yielding improved fluidics, better and more effective energy delivery, and different types of power modulation² that lead to less use of ultrasound (US), fewer complications, and better surgical outcomes. Different modalities of US are also available, including a longitudinal mode, which oscillates the cutting/aspirating tip in a forward-and-back motion, and a torsional mode,

which is a more recent innovation that creates a side-to-side movement of the tip.

High-speed video technologies, usually referring to faster than “normal” video recording rates (where normal are frame rates ranging between 25 and 60 frames per second), have been successfully used to study the fluidic dynamics of phacoemulsification systems.^{3–6} Other engineering techniques, such as particle image velocimetry, have been used to evaluate flow patterns in different medical fields such as hemodynamics^{7–9}

and to characterize acoustic streaming.¹⁰ Particle image velocimetry is an optical technique for flow-velocity measurement that uses vector analysis of particles in motion measured in a cross-section of a flow.

The purpose of this study was to describe the fluid dynamics occurring in a simulated anterior chamber and to describe the tip-to-tissue interaction during phacoemulsification with longitudinal or torsional modalities using high-speed videography, particle image velocimetry, and a hyperbaric environmental system.

MATERIALS AND METHODS

Fluid Dynamics

Ultra-high-speed videos, approaching rates in the hundreds of thousands of frames per second (fps), were recorded while a mini-flared Kelman tip with a 45-degree bevel (Alcon Laboratories, Inc.) was operated in longitudinal and torsional modalities using a control driver and a peristaltic pump between 0% and 100% US power in a poly(methylmethacrylate) rectangular test chamber with flat optical-quality walls with 45.0 mm × 12.5 mm × 12.5 mm dimensions, a 10.0 mm × 35.0 mm window size, and a volume of 4.5 mL (Plasti-Brand disposable cuvettes, 4.5 mL, Sigma-Aldrich Co.) (Figure 1). Two high-speed video cameras (Fastcam SA1.1, Photron, Inc.) were used to record viewable video at speeds up to 625 000 fps (Figure 1). One camera recorded in black and white (a mode that required less light), and the other camera recorded in color (a mode that produced better images but required more light). The maximum speed was limited by the available light. A high-intensity spotlight source was used for illumination to engage shadowgraphy techniques. Neutrally buoyant polyamide beads (polyamide seeding particles, diameter 20 μm, density 1.03 gr/cm³, Dantec Dynamics A/S) were seeded into the liquid medium (distilled water) to characterize flow and to allow particle image velocimetry. Flow speed was calculated by detection of bead position shift in pairs of digitized images with known time separation using a ruler tool (Photoshop, Adobe Systems, Inc.) under set magnification. Direction and speed were then calculated with knowledge of frame rates (16 000 fps, 75 000 fps, and 250 000 fps) and camera pixel size (12.8 μm, 6.4 μm, and 3.2 μm) for the set magnification (×2.5, ×5.0, and ×10.0).

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Cavitation

Cavitation was evaluated with a video technique that used a system of synchronized lighting with recording speeds up to 625 000 fps and a previously described environmental hyperbaric system³ that consisted of a test chamber (a tubular acrylic shape with a piece of flat glass to allow viewing) pressurized using a syringe pump that allowed the control of environmental pressure surrounding the system to suppress the onset of cavitation bubbles. A constant, uniform pressure was applied against all components while ensuring proper function of the handpiece. The pressure level was controlled and monitored continuously using a computer interface that consisted of a computer notebook with a Universal Serial Bus (USB) data-acquisition board adaptor with analog and digital input and output signals (DAQ Board Model USB-1208FS, Measurement Computing Corp.) connected to a pressure sensor (Sensor press 4 bar gage, NSC DigiKey, Honeywell Sensing and Control). All pressures are reported above atmospheric pressure (0 bar). Individual cavitation bubbles were detected using the Photron high-speed cameras. All hyperbaric studies were performed using a stroboscopic lighting system that showed cavitation using standard 29.97 fps recording speed. Cavitation was also recorded at different US power settings to examine differences between longitudinal and torsional modes with respect to the characteristics of the origin of cavitation. Selected scan lines from sequential video frames were arranged along a timeline to produce composite images illustrative of the amount of cavitation at a given time and setting (similar to M-mode US displays) as previously described.³

Tip-to-Tissue Interaction

The same test chamber setting described to assess fluid dynamics was used to evaluate tip-to-tissue interaction. A tube was filled with intact human cataract material that had been collected more than 3 years before the experiment after routine extracapsular cataract extraction procedures performed by 1 of the authors (J.Z.) and preserved in a balanced salt solution at 4°C. This material was then placed in front of the phacoemulsifying tip inside the test chamber while steady vacuum was built through the lumen to attract and hold the tissue. Ramps of longitudinal and torsional US power at 10% increments between 0% and 100% were applied to the phacoemulsifying tip ranging from 0.0 to 3.5 mils (0.0035 inches or 90 μm) in pulses lasting 0.5 to 2.5 seconds. High-speed video recording of the phacoemulsification of the human cataract fragments using both US modalities was played back at slower frame rates to allow visualization of tip-to-tissue interaction that was improved over visualization with traditional video-recording playback (eg, 30 fps).

RESULTS

Fluid Dynamics

Ultra-high-speed video recording of a closed irrigation/aspiration system set at a rate of 20 mL/min showed 2 diverging irrigation streams, each with a speed up to 0.9 m/s on exiting the infusion ports of the irrigation sleeve. These flow streams were directed to each side of the phacoemulsifying tip at a 30-degree angle, approximately. In this closed system, the tip aspiration port removed an equal volume of 20 mL/min

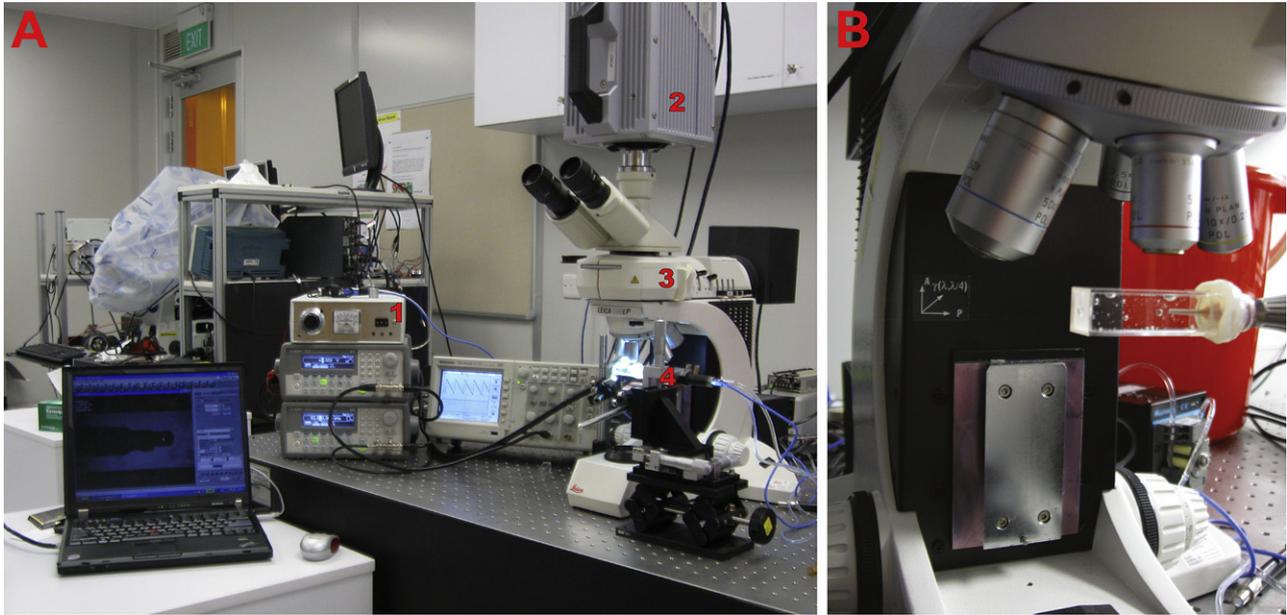


Figure 1. Electro-optical setting. *A*: Ultrahigh-speed video recorder capable of up to 1 million frames per second. (1) Phacoemulsification driver (US generator stack). (2) High-speed video camera. (3) Light microscope ($\times 2.5$ to $\times 10.0$). (4) Torsional/longitudinal handpiece. The setting included a fiberoptic illuminator (not shown). *B*: Acrylic test chamber.

with a maximum speed of 0.25 m/s. Adding US power to either modality did not appear to interfere with the flow pattern of irrigation and aspiration at lower power settings (ie, less than 30% power for longitudinal mode, less than 50% power for torsional mode). However, increasing the US power produced disruptive fluid streams and different footprints for longitudinal and torsional modalities. Longitudinal US between 40% and 100% power produced a far-reaching stream that appeared in front of the tip moving in the opposite direction of aspiration, producing a repulsive effect on the beads (Video 1, available at <http://jcrsjournal.org>). The transition from the normal flow pattern to the disruptive flow was seen between 30% and 40% power, and it occurred in an abrupt manner. The maximum flow speed of this stream was 1.9 m/s. When torsional power was increased above 80%, a fluid stream appeared; however, it was directed toward the rear portion of the phacoemulsification probe (Video 2, available at <http://jcrsjournal.org>), producing what appeared to be an attraction effect on the beads. Torsional showed a smooth transition between the non-US flow pattern, and the disrupting pattern as power increased between 50% and 80%. The maximum flow speed of this stream also reached 1.9 m/s.

Cavitation

Cavitation was evident with both US modalities at moderate and high power settings. Longitudinal mode was associated with steady cavitation above

a threshold value of 60% US power, while torsional mode produced steady cavitation with US power above a threshold value of 80% (Figure 2). Furthermore, under hyperbaric pressures, cavitation from longitudinal US gradually decreased with increasing pressure and complete bubble formation was suppressed with pressure above 1.0 bar. With US set at maximum power, cavitation from torsional mode was completely inhibited with only a slight increase in pressure to 0.3 bar. In addition, minimal changes in pressure around the threshold showed that cavitation appeared and disappeared in a pressure-dependent and reversible manner (Figure 3). This effect was not seen with longitudinal US.

When using a recording speed rate near 500 000 fps, the video played back at slower rates showed that collapsing cavitation bubbles from either modality induced the formation of satellite miniature bubbles. These satellite bubbles closely followed the US-induced streams of fluid previously described. The miniature bubbles did not appear to behave like the previously described “normal” cavitation bubbles; instead, the miniature bubbles appeared stable over a longer period and did not collapse further (Video 3, available at <http://jcrsjournal.org>).

Tip-to-Tissue Interaction

When closely examining the interaction of lens material against the ultrasonically oscillating cutting tip, there were noticeable differences between longitudinal and torsional US with US power in the range of 70% to

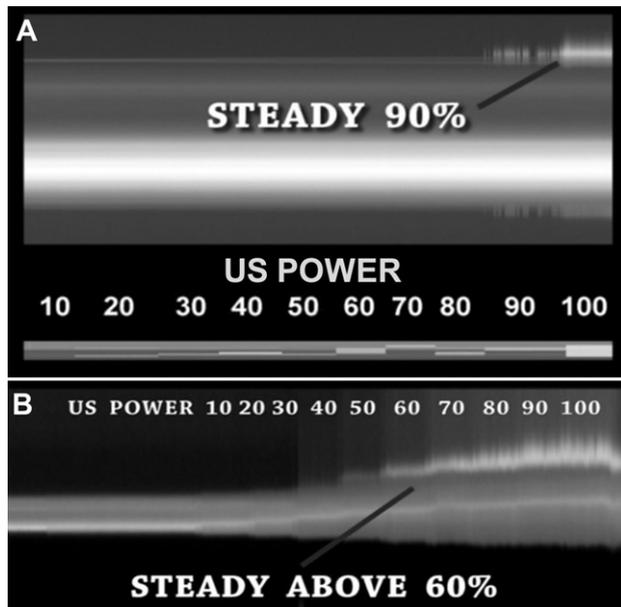


Figure 2. Line scan composite image showing cavitation as a *white* cloud near the tip's distal end in response to increasing US power levels. Stable cavitation was observed at different US powers for the 2 US modalities. A: Torsional. B: Longitudinal.

100%. Repulsion was evident with longitudinal mode as the cataract fragment bounced repeatedly in front of the phacoemulsifying tip (Video 4, available at <http://jcrsjournal.org>). Torsional mode allowed better settling of the cataract fragments on the phacoemulsifying tip's opening (Video 5, available at <http://jcrsjournal.org>) and appeared to maintain attraction with the lens material even as the torsional US would occasionally reposition the fragment without repulsion until the fragment was sufficiently eroded.

At high US power (above 60% for longitudinal and 80% for torsional), both modalities produced cavitation bubbles near the interface between the tip and the cataract tissue. On closer inspection of either modality in action, cavitation bubbles were seen collapsing near small fragments of cataract tissue already detached from the main piece of lens by mechanical impact of the metal to the tissue. In addition, cavitation bubbles did not seem to collapse in close proximity to the tip-tissue contact area; therefore, the tip appeared to be the only mechanism to apply damage to the lens material on mechanical impact, even when in close proximity to the location of the bubbles, thus indicating that the energetic bubbles were not involved in the emulsification process (Video 6, available at <http://jcrsjournal.org>).

DISCUSSION

Phacoemulsification uses high-intensity US energy to fragment and emulsify the lens. This study showed

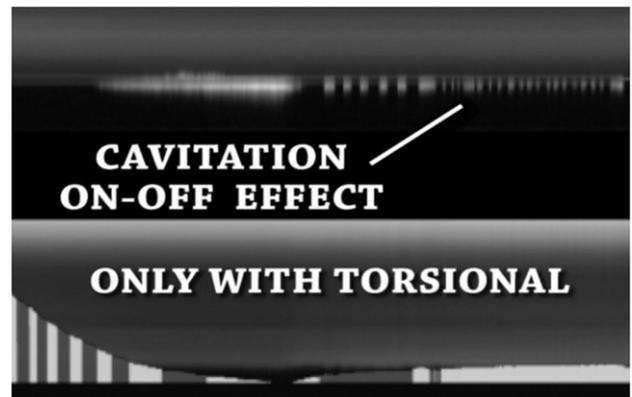


Figure 3. M-Mode type illustration showing cavitation as a *white* cloud near the tip surface. The lower recording in *gray* and *white* vertical stripes represents pressure. (Each stripe *color* transition represents a 0.1 bar transition step.) Cavitation was totally inhibited when pressure increased above 0.3 bar and reappeared suddenly when pressure dropped below said threshold. Small fluctuations of pressure around this threshold produced an on-off effect, rapidly shifting between evident cavitation and no cavitation, as shown to the right of the picture's upper tracing.

that this energy can also be transformed to create interesting and identifiable movement of the fluid. Using particle image velocimetry, we were able to observe and quantitatively describe the events that occur in a simulated anterior chamber during phacoemulsification with longitudinal and torsional US modalities. Our findings using this technique are similar to those reported by other authors.^{5,6} Miyoshi and Yoshida,⁵ using ultra-high-speed videography and a test chamber, reported that the movement of the tip with longitudinal US moved the lens material away; this repulsion induced chattering and increased tip travel, whereas torsional US maintained the lens material at the tip for aspiration. Although their focus was on the movement of the lens material with respect to each US modality tested, our findings further support their hypotheses through the understanding of the observed and measured fluidic dynamic behaviors. They also reported the presence of cavitation bubbles in both modalities at the opening of the phacoemulsifying tip, with each US type showing a different configuration. However, our research suggests that these bubbles have little influence on lens removal during phacoemulsification.

In a study that used neutrally buoyant beads to trace fluid flow in a test cell, de Castro et al.⁶ found that when longitudinal US was used, the majority of the beads attempting to be aspirated were repelled and the overall material removal rate (or aspiration efficiency) was reduced. When torsional US was activated, aspiration of the beads occurred without repulsion. Our study supports the presence of a fluid stream during longitudinal phacoemulsification that

added a repulsive force, as seen by bead movement and under scrutinized tip-to-tissue interaction. In addition, we describe the possibility of a weak attractive force that may result from rearward-moving fluid streams that were only produced by torsional US.

Cavitation^{11,12} and the jackhammer effect^{3,11-13} are theories that have been proposed to explain how the phacoemulsification mechanism works. Cavitation refers to a form of localized high energy that can be produced by US probes¹² and is characterized by rapid formation of small bubbles that later collapse, releasing that energy to its surroundings. The jackhammer effect is meant to serve as analogy to the mechanical impact of the phacoemulsifying tip against lens material. In a previous study,³ it was determined that the mechanical cutting of the jackhammer effect using longitudinal US dominated the emulsification of the lens material, whereas cavitation contributed little, if any, effect to emulsification. Similar to the previous experiment,³ the present study also used visualization techniques in a hyperbaric chamber to investigate the cavitation phenomena. This study determined comparatively that the cavitation bubbles originating from a probe tip under torsional movement created more fragile cavitation, as evidenced by its ease of suppression under lower elevated chamber pressures. Under ultra-high-speed videography with synchronous lighting methods, the same differences between cavitation and mechanical cutting, as well as differences between longitudinal and torsional US, were distinguishable as the tip contacted the lens material. Again, this showed that while the cavitation bubbles were present, they were not responsible for the majority of cutting.

This study along with others have shown that the presence of cavitation can be detected and comparatively quantified by using video recording systems.^{3,11} Other researchers have made similar comparisons by directly monitoring the generation of free radicals, sonoluminescence, and/or by selected hydrophone or acoustic systems.¹³ Using free radicals as a representative tracer for the detection and measurement of cavitation has been accepted. Although this and previous studies have shown that cavitation does not contribute significantly to the emulsification of the lens tissue,³ it has been found that the generation of free radicals, a byproduct of cavitation during phacoemulsification, can damage the corneal endothelium.^{14,15} Similar studies also determined that the amount of US power used correlates with the amount of free radicals generated.¹⁵⁻¹⁷ Our study also shows that US power correlates with cavitation production.

One approach to protect the corneal endothelium is to suppress or capture free radicals that may be present by using antioxidants such as ascorbic acid¹⁸ and

glutathione.¹⁹ Experimental studies by Aust et al.^{20,21} found that torsional US produced fewer free radicals than longitudinal US. Therefore, using a US modality that produces fewer free radicals such as torsional could also provide a protective effect by suppressing free radicals at the source. In parallel support of Aust et al.'s findings,^{20,21} we found in the present study that cavitation generated by a torsional phacoemulsifying probe was more fragile than cavitation generated by longitudinal US, which again correlates to lower free radical production.

In summary, this multifaceted experiment found differences between longitudinal and torsional US with respect to fluid movement in a simulated anterior chamber and the intensity of cavitation produced by either modality. The results support the work of others that longitudinal US can repel material with a forward-moving fluid stream. In addition, the study adds to the theory that torsional US not only does not repel material at the tip but may create fluid dynamic mechanisms to attract material. In addition, this study reinforces the theory that mechanical cutting dominates cavitation effects as the mechanism for emulsifying cataractous material.

WHAT WAS KNOWN

- Phacoemulsification uses high-intensity US energy to fragment and emulsify the lens.
- Lens material removal is different with longitudinal US versus torsional US.

WHAT THIS PAPER ADDS

- This experiment provided video evidence using a simulated anterior chamber to show how longitudinal US produces repulsive fluid streams while torsional US does not.
- While both US modalities produced cavitation bubbles, neither demonstrated through visual evidence that these bubbles contributed to emulsification of lens material.

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