PHYSICS OF PHACOEMULSIFICATION

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Abstract

The phacoemulsification mechanism using high power ultrasound remains the subject of debate. It is generally attributed to either cavitation or mechanical forces. Measurements were made for a commercial phacoemulsification unit operating at 40 kHz. Tip radiation patterns were imaged in water. The far-field was measured during operation using wide-band receivers attached to tissue phantoms and freshly enucleated porcine eyes. Operating in the normal clinical range a minimal level of random cavitation was detected. These emissions remained at low levels, even at higher powers. The number of cavitation events detected reduced with increase in tissue hardness. In pulse mode, no evidence was detected for "transient cavitation." The characteristic "cavitation hiss" was audible. The source of this sound was found to be at the horn shoulder. It is concluded that the primary mode for tissue disruption using a phacoemulsification unit employing a straight bevelled ended tip is due to a "jack-hammer" effect.

Introduction

Within parts of the phacoemulsification community, the mechanism of tissue fragmentation has long been attributed to a combination of mechanical impact (jack-hammer effects), shock waves in a fluid, the surface impact of particles and possibly cavitation [1]. Others still claim that cavitation is the dominant mechanism and that with pulse (tone-burst) excitation transient cavitation occurs at the start of each pulse. Schafer has stated that cavitation, or micro-bubbles collapsing, breaks up tissue and this is "the principal mechanism of phaco-cutting" [2].

Within the ultrasonic surgery community, it was initially assumed that because the devices were derived from those produced by Cavitron, and the original papers in the field made the statement that cavitation was the mechanism; then this must be the case. When the scientific literature is reviewed, it is apparent, particularly in the surgical literature, that "cavitation" is assumed. At best, this statement is based on minimal scientific observations, and in most cases no evidence or data are given to support the statement. The cavitation mechanism for phacoemulsification, and other procedures that employ tissue fragmentation, has become the assumed mechanism and this has propagated more as "folklore" than based on firm science.

Several studies have been performed seeking to answer the mechanism question, both for phacoemulsification and for other procedures that use devices based on the same physics [3, 4]. In diverse procedures that use a device similar to that in Figure 1, the interaction's fundamental physics is the same. A hard vibrating tip is used to cut or shatter hard tissue or to cut or emulsify soft tissues [5]. In surgical practice, if a flat-ended tube is employed, the tip is commonly set at an angle to the surface to "machine away" tissue. In phacoemulsification, a variety of bevelled tips are employed to achieve the same effect. The use of non-normal incidence and a bevelled tip significantly increases the range of tough tissues that can be fragmented and lowers the power (amplitude) at which cutting is initiated for a particular tissue [6].

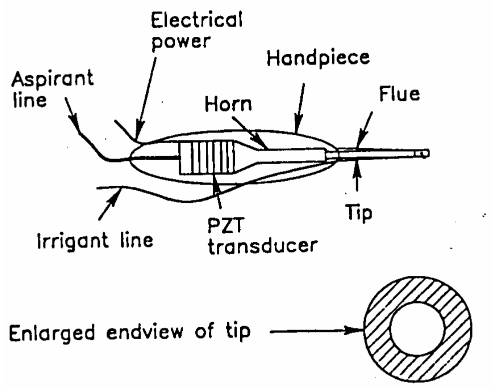


Figure 1 : Schematic for a phacoemulsification hand piece, including tip (ultrasonic horn).

The Bond and Cimino study [3,4,7,8] has been reviewed and cited by other authors. It has been described recently by Boukhny [6] as a "very detailed study which proved beyond the shadow of doubt that cavitation plays no useful role in phaco or other cutting ultrasound applications." And yet the debate regarding the mechanism of phacoemulsification, and other procedures based on ultrasonic tissue fragmentation, continues.

Fundamentally, the mechanism question is this: Does the scientific data identify cavitation or a mechanical jack-hammer as the primary mechanism? The primary objective for the present study was to review prior work and investigate the performance of a phacoemulsification unit operating under clinical conditions. The study specifically looked for cavitation and sought to definitively demonstrate what is the primary mechanism for tissue fragmentation in phacoemulsification.

Mechanisms and Interaction Zones

There are three basic classes of phenomena identified when analysing ultrasonic horn-tissue interactions: a) **non-cavitating and mechanical forces**—including impacts, radiation pressure, acoustic streaming, and hydrodynamic shear; b) **thermal**—absorption and heating; and c) **cavitation**— and related micro-bubble activation. All these phenomena are non-linear.

The tip-tissue interactions then occur in "zones" that can be defined moving out from the horn-tip. The zone size depends on horn-tip geometry, the power level and frequency of operations with the distance scale defined by the ultrasound wavelength. At 40 kHz, the wavelength in tissue is ~39mm (~1.5 inch). These interaction zones are then: 1) the **tip-tissue mechanical interaction**—which extends less than 500 microns into the impacted tissue (small fraction of a wavelength); 2) intermediate **mechanical forces zone**—which extends in an eye undergoing a phacoemulsification procedure at surgical power from about a millimeter to a centimetre or more. This is where there is significant radiation pressures that will cause acoustic streaming, debris, or particle motion in fluid; and 3) **thermal zone** or "far-field"—where the ultrasound is converted to heat through absorption. This is typically, all parts of material beyond those regions where ultrasound interacts for highly non-linear interactions in zones 1 and 2. There will also be reflections at fluid-tissue and tissue-air interfaces which will complicate the ultrasonic field within a limited structure, such as the eye.

System Characterization

The study of the CUSA 200 included combinations of tissue removal effectiveness, ultrasonic, thermal, and electrical measurements, supplemented by high-speed photography. The ultrasonic horn tip vibrates at 23 kHz with peak amplitude of about 330 microns. This gives a tissue impact velocity of 22 m/sec. This work demonstrated that tissue disruption with a horn (tip) with circular cross-section occurs on the forward stroke and can be related to mechanical forces [3,4,7,8] – a "jack-hammer effect."

The commercial phacoemulsification unit used operates at 40 kHz. Procedures were performed with various directional tips, operating at a range of powers, in both continuous and "pulse" (tone-burst) modes. The peak tip amplitude is 100 microns. The unit was used with both irrigation and aspiration setting within the normal clinical ranges.

Radiation Pattern – in a water bath

The radiation patterns were imaged in a large water bath using a scanning wide-band hydrophone. The acoustic field exhibits directivity which depends on power levels. At 1 cm below the tip and 100% power a "dough-nut" shaped field is produced, which includes a dilute stream of micro-bubbles on axis. When dye is used to visualize acoustic streaming a complex near-cylindrical flow pattern is produced which is consistent with earlier reports for acoustic streaming fields [9].

Ultrasonic field measurements

A commercial phacoemulsification unit, was operated with straight 45-degree bevelled tips [6] in both continuous and pulse (tone-burst) excitation and both with and without irrigation and suction (aspiration). The non-irrigated mode is not recommended as the tip heats very rapidly! Various ultrasonic measurements were made with three types of samples: hard and soft tissue phantoms and fresh porcine eyes.

a.

b.

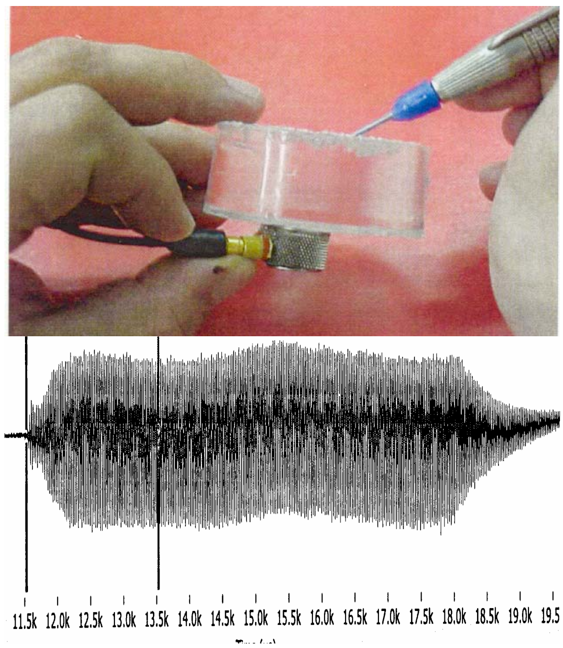


Figure 2 : Measurement configuration (a) on hard-tissue phantom and (b) example of digitized data record in "pulse" mode – showing gate used in early record FFT.

A hydrophone, a wide-band receiver, with effective bandwidth from below 10 kHz to 2.25 MHz was used to record the ultrasonic signals [2,3,7,8]. The ultrasonic waves produced by the horn-tip sample impact are a 40 kHz sine wave. This fundamental at 40 kHz couples from the horn-tip and with any acoustic emission (cavitation signals) propagates through the test sample to the receiver in the configuration as shown in Figure 2a.

The hard tissue phantom (puck) was fragmented using both pulse and continuous operation. Acoustic data were recorded and a Fast Fourier Transform (FFT) used to provide spectra. A gate was used to select segments of the record for processing. An example of a spectrum is shown in Figure 3. No differences were seen between spectra from continuous or pulse - early, mid and late record data. As a result of significant data record review some occasional random possible cavitition events were identified but there was no evidence of significant cavitation noise. Similar results were obtained with a soft-tissue phantom.

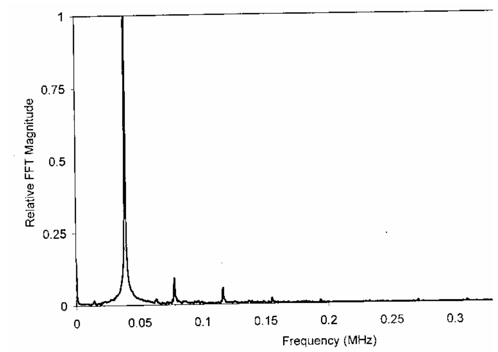


Figure 3 : Spectra from early FFT (Figure 2b).

Measurements on porcine eyes

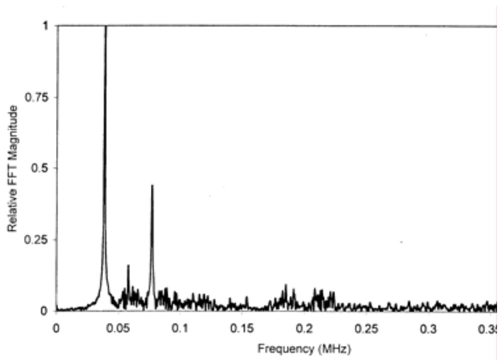
Measurements were made on fresh (as received) and treated eyes, where a brief micro-wave treatment was used to harden the lens. The eye was attached to a shaped foam base that included the same transducer as used with both the hard and soft tissue phantom measurements.

The phacoemulsification procedure was performed using standard clinical protocols [6] and the configuration is shown as Figure 4. The unit was operated under a range of conditions, including full power, 40% power, both with and without irrigation and aspiration. The unit was operated for different procedures with both continuous and pulse (tone-burst) excitation.

Digitized received acoustic signals were gated and processed using an FFT. The spectra produced exhibited a strong fundamental, higher harmonics and some low-level cavitation noise. An example of a spectrum is shown in Figure 5a. The energy partition between harmonics varied during a procedure, and when working in pulse-mode was not dependant on gated data being early, mid or late pulse record. For a tough lens it was found that there was an increase in the energy converted to higher harmonics, as shown in Figure 5b. The magnitude of the cavitation noise remained at a low level and similar under similar conditions {the data in Figure 5 are shown normalized against maximum spectral peak height}.

Figure 4 : Photograph of phacoemulsification on porcine eye.

a.



b.

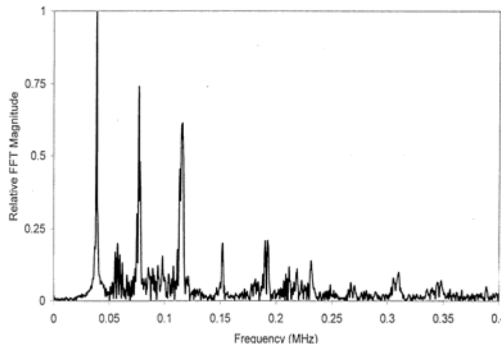


Figure 5 : Spectra for a porcine eye with unit in pulse-mode. a. Spectrum for early data at 40% power. b. Spectrum on hard lens, mid-record data, at 40% power.

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.

Cavitation "hiss"?

During the procedures reported above, the team did hear an audio "noise" that has been attributed to being a "cavitation hiss." However, the measured data only exhibited evidence of low levels of acoustic noise. For measurements in water when operating at clinical power levels, there was no obvious strong cavitation below the horn-tip. This apparent contradiction was investigated. If the cavitation events are not occurring at the tip during phacoemulsification, as indicated by the spectra, what is the source of the characteristic audio "cavitation hiss?"

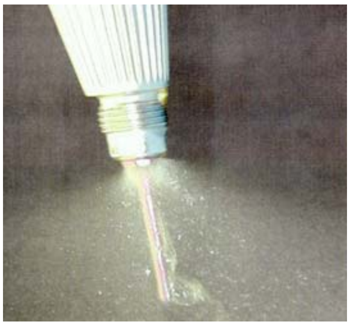


Figure 6 : Atomization and source of "hiss" from shoulder of tip.

A series of experiments were performed. The hand piece was operated without irrigation—it still cuts—and under these conditions there is no audible "hiss." The unit was then operated with irrigation and no flue and the hiss occurs. The shoulder at the top of the horn is the source of a fine atomized mist as shown in Figure 6. The hiss only occurs when the shoulder of the horn is immersed in fluid or the flue is in place, which entrains irrigation fluid. Further investigation showed that some low-level cavitation events do occur near the tip when the irrigation fluid has transported micro-bubbles down the flue and this is probably due to "micro-bubble activation" [7], and not cavitation at the horn-tip.

Conclusions

It is shown that the perceived cavitation "hiss" is not due to cavitation in an eye during phacoemulsification. The findings of the 1994-96 [2,3,7,8] and most recent work are consistent. No evidence was detected that supports claims that cavitation is occurring at the tip-tissue interface. Claims of cavitation being the mechanism at the power used in phacoemulsification are unsupported. There is no evidence of transient cavitation occurring when units are operated in pulse mode. The physics of the tip-tissue interaction is the same in both a pulse and a continuous-tip excitation mode. The fluids used for irrigation are important in thermal management. Tip designs and pulse (tone-burst) operation serve to reduce the power needed to give effective tissue disruption (cutting). The audible cavitation "hiss" emanates from the horn shoulder and not the tip-tissue interaction zone.

The observations all support the hypothesis that the primary mode for tissue disruption is due to a jack-hammer effect.

Acknowledgement

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