Phaco-emulsification causes the formation of cavitation bubbles

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Abstract

There have been reports of complications arising from damage to non-lenticular ocular tissue during the increasingly popular procedure of cataract extraction with phaco-emulsification. One cause of this damage might be the formation of cavitation bubbles. Such bubbles are known to produce free radicals and shock waves. This paper demonstrates directly the formation of cavitation bubbles at the tip of the phaco-probe. It also shows the importance of a smooth probe profile in reducing bubble formation. Recommendations are made for probe and tip design and for the use of minimum power during the surgical procedure of phaco-emulsification. Curr. Eye Res. 13: 649–653, 1994.

Key words: phaco-emulsification; cavitation; free radicals; tissue damage

Introduction

The advent of phaco-emulsification by an ultrasonically activated probe inserted into the cataractous crystalline lens was pioneered by Kelman in 1967 (1, 2). The technique is now widely used and its difficulties and likely shortcomings have been extensively documented (3). However, like many new procedures, its introduction and refinement of technique has involved empirical development, although theoretical and technical analyses have guided instrument design (4, 5).

The way in which the phaco-probe acts has been thought to be like a jack hammer, the tip reciprocating and 'chipping' out pieces of lens nucleus (6). For maximum effect, the probe must be in good contact with the lens substance, and any intervening gas will seriously compromise the cutting power of the probe tip. Consideration of the amplitude and frequency of tip movement suggests that the tensile strength of the tissues or irrigation fluid may be exceeded so that cavitation bubbles might be formed (7, 8). If such bubbles are formed, the tip would be uncoupled from the tissues and its effectiveness reduced.

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Cavitation bubbles induced by high power ultrasound have been thoroughly studied for some years (9). Energy is stored in the bubbles and is subsequently released generating high pressures ($\geq$ 1000 bar) and high temperatures ($\geq$ 5000°C). These high temperatures and pressures lead to the induction of free radicals which might be deposited in tissues causing damage in unwanted and unexpected locations (10–12).

To see if cavitation occurs during phaco-emulsification, we used a high framing rate camera to investigate the formation and location of bubbles induced by the probe of a popular *state of the art* phaco-emulsification instrument. This paper reports the first direct demonstration of the generation of cavitation in phaco-emulsification.

Methods

A phaco-emulsification probe with a nominal operating frequency of 40 kHz (OMS Diplomate, OMS Corporation, Boston, MA) was mounted with its tip beneath sterile saline in a small PMMA curvette (25 × 25 × 35 mm). A number of different probe designs were tested. For some of the trials the silicone irrigation sleeve was removed to allow clearer observation of cavitation at the junction of the probe and the handpiece. Photographs were taken on Polaroid film at either 10^5 or 10^6 frames per second (Imatronic high framing rate camera type 790, Hadland Photonic, UK). Pictures were made through magnifying optics, using frontal or back lighting provided by slow burn magnesium filament flash bulbs (Sylvania type 3), during the periods that the probe was activated. The irrigation of the probe by saline was sometimes turned off to prevent bubbles that formed from being swept out of the field of view. In one experiment, the saline was replaced by unfiltered tap water. Exposures were made with the power setting of the phaco-emulsifier set at different percentage levels according to the controls on the instrument.

Results

Figure 1 shows that cavitation bubbles can be formed at the tip of the probe in saline. It was not possible to establish a definite value for the threshold power for cavitation because:

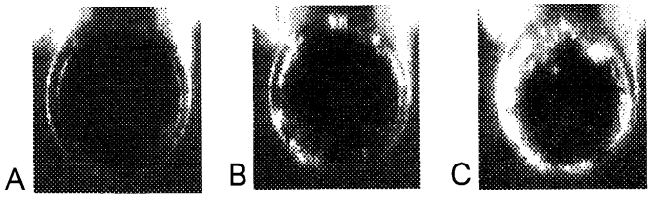

Figure 1. Frontal view of the tip of a standard phaco-probe in saline operating at power settings of a) 60%, b) 75% and c) 100%. These frames are from several series made at 10^5 fps and have an exposure duration of 2 μs. The diameter of the tip is 1.08 mm and its face area is 0.23 mm^2. Note that in **A**, the power setting is below the threshold and no bubbles can be seen; in **B** bubbles are present and in **C** they are very obvious.

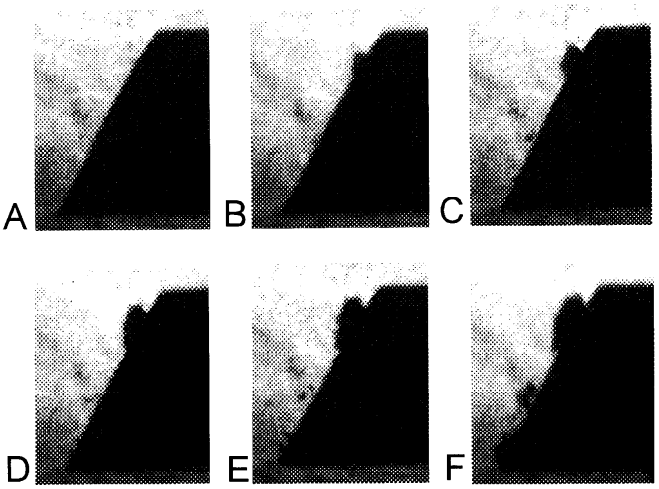

Figure 2. A series of six side-view pictures taken at 10^6 fps and 100% phaco-power showing the formation of cavitation bubbles on the probe tip in saline. The series is during the negative stroke of the cycle and lasts about 7 μs, which is about one third of a cycle of oscillation. The time sequence is indicated by the letters A through F. There are silhouettes of bubbles in frames B through F in increasing numbers.

a) bubble formation is subject to statistical variation so a probit analysis would be required but resources were not available for this, nor is it necessary for a demonstration that cavitation is present,
b) the inter-framing interval of the camera meant that a considerable fraction of each cycle of tip reciprocation was lost in the recordings,
c) the power output of the OMS Diplomate was adjustable only in 5% steps and
d) the resolution of the optics and camera (about 10 μm) meant that small bubbles expected at threshold would be missed.

However, the threshold was estimated to be about 70% ± 5% phaco-power. Replacing the sterile saline with tap water, which contains dust, impurities and dissolved gasses, did not noticeably lower the threshold.

Bubbles, once formed, did not last for a complete cycle of tip reciprocation as shown in Figure 2. They were either swept away by the flow of the irrigation fluid or collapsed after a lifetime of several microseconds. The exact duration of the bubble depends on the ultrasonic frequency and bubble diameter (10–12).

Figure 2 shows the formation of cavitation bubbles in the negative or back-stroke of the probe cycle when a void was created in front of the tip. The figure only covers the first third of a cycle from the point of maximum extension in the first frame. Figure 3 is a series of six photographs at the lower framing rate which spans about two and a half cycles. At the top of the frame is shown a fixed point which serves as a measuring reference. Analysis of the series like that in Figure 3 established the amplitude of oscillation as approximately 80 μm, and that bubbles form on the negative stroke and disappear or collapse during the early stages of the positive or forward stroke.

When a probe with a larger surface area was used (smaller internal bore than the probe in Figure 1, face area = 0.46 mm^2), the threshold for cavitation was reduced. Cavitations could be seen on such a tip at 60% phaco-power (Figure 4). The

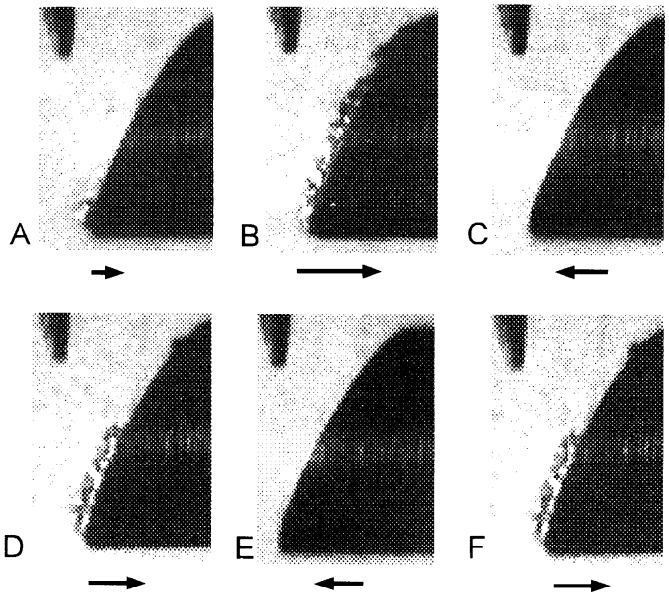

Figure 3. Six side-view photos made at 10^5 fps and 100% phaco-power showing the formation of bubbles on the negative or back stroke of the tip. The diameter of the tip is 1.08 mm and the measured amplitude of oscillation is slightly less than 80 μm. The series covers about two and a half cycles of the tip oscillation and clearly shows the appearance and disappearance of the bubbles. The arrow under each frame indicates by its direction and length the direction and an estimate of acceleration of the face of the tip.

surface area was one of the major factors determining threshold for cavitation at the phaco-tip.

During phaco-emulsification, cavitation bubbles are frequently seen in the anterior chamber. The source of these bubbles is likely to be at the shoulder of the probe and the junction with the hand piece (usually a screw fit). These features are hidden by the silicone sleeve so the bubbles are swept down into the eye with the irrigation fluid. The threshold for bubble formation at these locations is considerably less than at the tip of the probe. We estimated threshold for formation of these bubbles to be between 30% and 40% phaco-power of the *OMS Diplomate*, the exact value depending on the shape of the shoulder and the efficiency of the coupling.

Figure 5A through D shows bubbles that are formed (with 100% phaco-power) at the shoulder of a probe with a conventional profile. In Figure 5E a probe with a streamline profile at the shoulder shows that no bubbles are formed there. There are, however, cavitation bubbles at the junction of the probe and the hand piece which are absent in Figure 5F where the probe was fully tightened in the hand piece. The possibility of bubble formation at scratches on the shaft of the probe was investigated, but we were unable to mark the titanium with more than very fine scratches and these did not form any bubbles, even at 100% phaco-power. Tips damaged by wear during long term use in surgery were also investigated but the threshold was not detectably reduced.

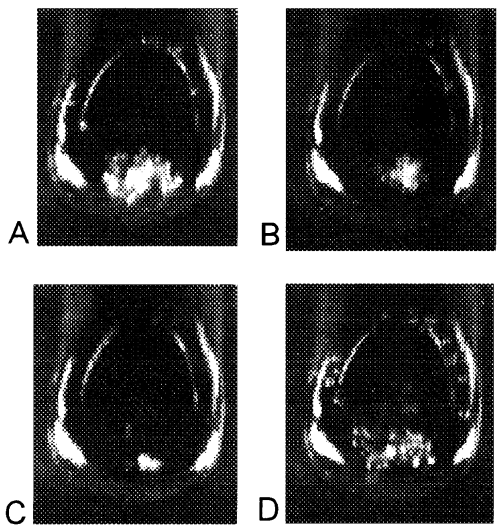

Figure 4. Four frontal view photos made at 10^5 fps and 60% phaco-power showing the formation of bubbles on a prototype tip with greater surface area (0.4 mm^2) than that in Figure 1. Bubbles are present in all frames but are especially obvious in A and D.

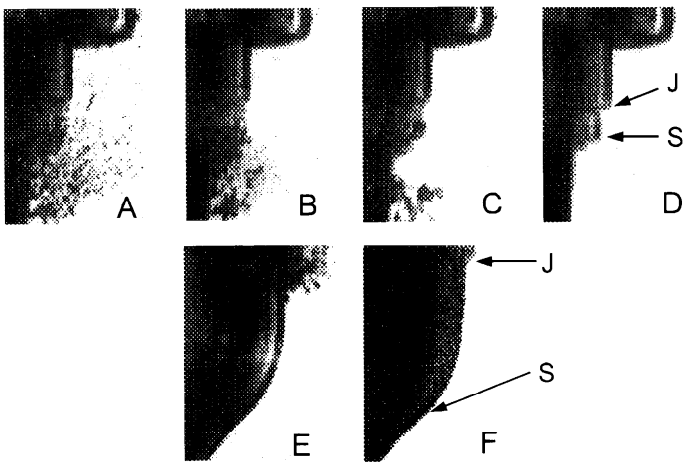

Figure 5. A through D: four frames from a series at 10^5 fps and 100% phaco-power of the probe shoulder and junction to the hand piece: note the cavitation bubbles at the shoulder and the junction as a cloud of fine bubbles in **A** which coalesce and collapse in **B**, **C** and **D**: the probe was of conventional design. **E**: as A through D but with a new design of probe where the shoulder has been modified to a more streamlined profile: note, no cavitation bubbles at the shoulder but a few at the junction of the probe with the hand piece where the probe was not fully tightened. **F**: as E but with tightened probe/hand piece junction: there were no cavitation bubbles at the either junction or shoulder. J = junction, S = shoulder.

Discussion

Despite the increasing popularity of phaco-emulsification in cataract surgery, the basic mechanisms underlying ultrasonic emulsification of the lens and the exact causes of damage to other ocular tissues are not fully understood. Phaco-induced damage to the corneal endothelium has been thoroughly studied (5, 13, 14) and correlated to the amount and duration of the ultrasonic energy delivered to the eye. The effects of small air bubbles introduced during phaco-emulsification have also been described (15, 16). The rapid forward movement of the phaco-probe tip during each cycle pushes fluid before it (ultrasonic pressure) and this might also have a deleterious effect on the endothelium. The chemical effects of ultrasound are well known phenomena caused by the extreme conditions of heat and pressure that arise during the collapse of cavitation bubbles.

In our study we could verify the induction of cavitation bubbles both at the probe tip and at the probe junction in conditions similar to those that apply during ophthalmic phaco-emulsification. These bubbles might:

a) impede coupling of the probe to the lens nucleus and lessen its mechanical effects, and
b) pose a more serious hazard to other tissues in the eye by transferring *bubble energy* to tissues remote from the probe tip.

It is believed that imploding cavitation bubbles will destroy cells in their vicinity by the shockwave or the release of free radicals (7–9, 12).

In our study we found cavitation to be related to the amount of energy delivered to the tip and to the surface area and profile of the tip. We therefore conclude that ultrasonic energy should be minimized during emulsification and that tips should be made streamlined with the smallest surface area to avoid unnecessary cavitations. Further studies in the field will be needed to correlate cavitation bubbles to collateral phaco-damage, and to find more efficient ways of protecting the eye from these effects.

Acknowledgements

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