High Intensity Focussed Ultrasound (HIFU)

At larger amplitudes than used in imaging, ultrasound has proved very useful in a number of medical contexts. High intensity focussed ultrasound (known as HIFU) with acoustic pressures of the order of $10 - 100 MPa$ causes the tiny cavitation nuclei present in all liquids and tissues (or perhaps placed there as ultrasound contrast agents) to become activated and cavitate. Such bubble dynamics are differentiated from those at lower intensities because they exhibit a period of uncontrolled bubble growth often referred to as *transient* or *inertial* cavitation. In some applications, it is the cavitation bubbles thus generated (rather than the ultrasound itself) that produce the clinical effect. In fact this is one of the most common interventionist uses of cavitation in medicine and is usually but not exclusively employed to denature or emulsify tissue.

Two different tissue destruction techniques using ultrasound are in widespread use. In the earliest applications an ultrasonically vibrating probe is placed in close proximity to the tissue or solid material. The cavitation induced at the tip of this probe creates the desired destructive or cleaning effect when it is placed close to the tissue or solid material. One of the earliest uses of such an ultrasonic probe was in dentistry, where ultrasonic probes are now commonly used to clean teeth by dislodging plaque. Another common use of an ultrasonic probe is in *phacoemulsification*, the procedure commonly used to emulsify and remove the natural optical lens during cataract surgery. A perfusion and vacuum system is built into the probe in order to remove the emulsified tissue. The invention of the phacoemulsification probe by Charles Kelman in 1967 was, in fact, motivated by the dental plaque-removing tool. The advantage of the phacoemulsification tool is that it can be inserted through a very small incision in the side of the eye and the old lens removed with minimal invasion (see figure 1). The new artificial lens is then inserted in folded form through the same incision and unfolded in place. More than a million such procedures take place each year. However, the WHO estimates that 17 million more people in the world presently suffer from cataracts. While problems with the procedure are rare, the main concerns are collateral damage to surrounding tissue and the possibility of damage to the material of the tool itself which might result in metal debris being left behind in the eye (Kelman (1967)).

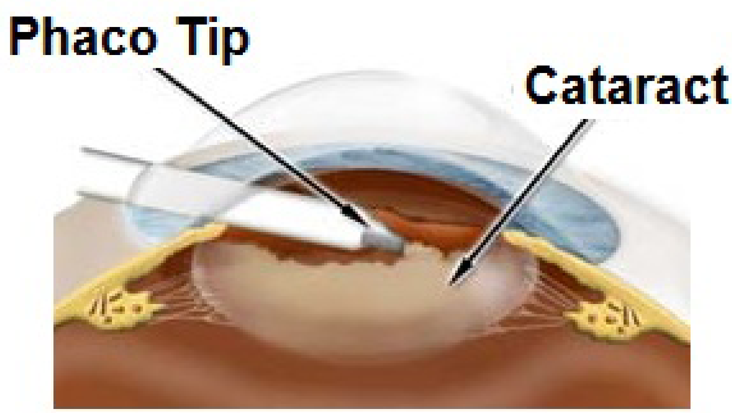

Figure 1: Schematics of the eye and of the phacoemulsification procedure.

Figure 2 is a frame from a high-speed video of a phaco-emulsification probe in use. It shows the cavitation on the $0.9mm$ diameter end face of the probe (or needle) as it approaches a cadaver lens (FDA (1996)).

Variations in the design of the probe have been deployed in attempts to increase its effectiveness and to minimize collateral damage by confining the cavitation to a well-controlled volume on the face of the device. One particular variation is particularly interesting from a fluid mechanical perspective. Anis (1999, 2003) has developed a probe that not only vibrates at ultrasonic frequency ($40kHz$ in this case) but also rotates (figure 2 is a view of this probe in action). Control over the extent of cavitation is important in minimizing collateral damage. In the absence of such control, cavitation can occur in unexpected and unwanted locations such as on the sleeve around the outside of the tool.

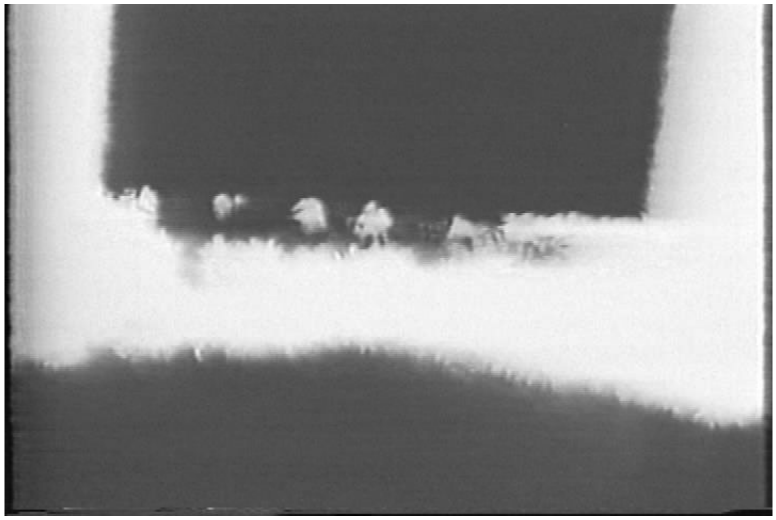

Figure 2: Outline of cavitation bubble cloud (the black images below the black rectangle) on the face of a phacoemulsifier (Anis (2003)).

The typical noise generated by a cavitation event on the face of a phacoemulsifier is shown in figure 3 (1999). The pulses shown superimposed on the first high pressure cycle of the ultrasound are very similar to the cavitation event noise measured in other hydrodynamic experiments; for example, figure 4 shows the prototypical signal produced by the collapse of a single cavitation bubble (Ceccio and Brennen (1991)) and includes the large positive spike produced by the first collapse as well as a second spike produced by the second collapse following the first rebound.

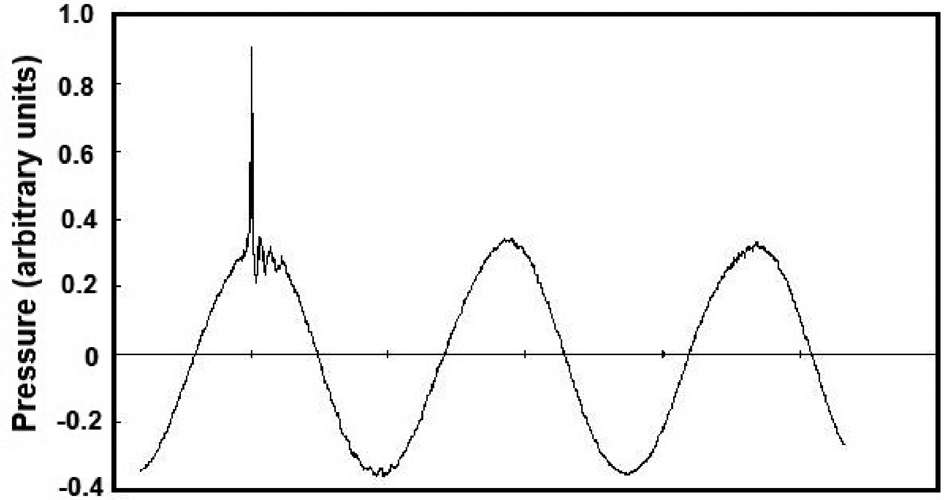

Figure 3: Typical phacoemulsification pressure signal showing a cavitation event during the first high pressure cycle (Anis (1999)).

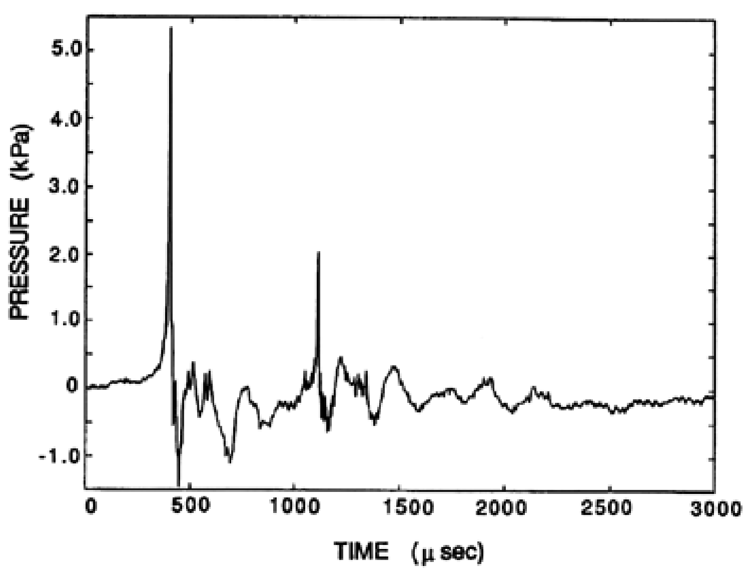

Figure 4: Typical acoustic signal produced by the collapse of a single cavitation bubble (Ceccio and Brennen (1991)).