BUBBLES, ULTRASOUND, AND SWIMMER SAFETY

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1 INTRODUCTION

The benefits of ultrasonics in algae control have been well known [1]. The transmit frequencies used to study this application have been as low as 20 kHz and as high as 1.7 MHz. Most commercial equipment operates in the lower ultrasonic range. There have been speculations about the physical mechanism behind the algae eradication, specifically about the role of cavitation.
Furthermore, the consequences for swimmers in water subjected to ultrasonic treatment have been unknown. In this study, we investigate the role of cavitation as potential danger for swimmers. Furthermore, we give an estimate of swimmer safety radii, based on current regulations.

2 CAVITATION

When a microbubble of radius r_0 is exposed to an oscillating acoustic signal, it undergoes alternate expansions and contractions with the same amplitude and duration at low driving pressures. Bubble activity that may occur at relatively low-amplitude pressures has been denoted as stable cavitation [2]. As the driving pressure increases, more complex nonlinear interactions occur; there is greater bubble expansion amplitude than contraction amplitude and relatively slow expansion followed by rapid contraction (collapse). This behaviour has been referred to as violent or inertial (or transient) cavitation [2].
For any driving pressure, there exists a transitional equilibrium microbubble radius, above which microbubbles pulsate like inertial cavities. This transition is referred to as the cavitation threshold. A bubble is judged to have grown into an inertial cavity when its maximum radius is greater than approximately twice its equilibrium radius [3]. For ultrasonic frequencies much lower than the resonance frequency of a cavitation nucleus (quasi-isostatic regime), the critical pressure p_c at which the cavitation threshold radius is reached has been derived in [4]:

$$p_c = p_0 - p_v + \frac{8\sigma}{9}\sqrt{\frac{2\pi\sigma}{k\,m_G T K_G}}, \qquad (1)$$

where k is Boltzmann's constant, K_G is the gas constant, m_G is the mass of the gas, p_0 is the ambient pressure, p_v is the vapour pressure, T is the temperature inside the bubble, and σ is the surface tension. This can be simplified to [5]:

$$p_c = p_0 - p_v + \frac{8\sigma}{9}\sqrt{\frac{3\sigma}{\left(2p_0 + \frac{4\sigma}{r_0}\right) r_0^3}}. \qquad (2)$$

On clinical ultrasound devices, the intensity of the ultrasonic field is generally adjusted with a switch for the mechanical index (MI), rather than the acoustic amplitude [6]. The MI is defined by

$$\mathrm{MI} = \frac{p^{-}}{\sqrt{f}}, \tag{3}$$

where p^{-} is the maximum value of peak negative pressure anywhere in the ultrasound field, measured in water but reduced by an attenuation factor equal to that which would be produced by a medium having an attenuation coefficient of 0.3 dB cm^{-1} MHz^{-1}, normalised by 1 MPa, and f is the centre frequency of the ultrasound normalised by 1 MHz [7].
For MI<0.3, the acoustic amplitude is considered low. For 0.3>MI>0.7, there is a possibility of minor damage to neonatal lung or intestine [7]. These are considered moderate acoustic amplitudes. For MI>0.7, there is a risk of cavitation if gas cavitation nuclei are present, and there is a theoretical risk of cavitation without the presence of cavitation nuclei [7]. The risk increases with MI values above this threshold [7]. These are considered high acoustic amplitudes.
If a bubble collapses near a free or a solid boundary, the retardation of the liquid near the boundary may cause a bubble asymmetry. This asymmetry causes differences in acceleration on the bubble surface. During further collapse, a funnel- shaped jet may protrude through the bubble, shooting liquid to the boundary [8, 9].
It has been noted, that, if microbubbles can create pores, it is also possible to create severe cell and tissue damage. Although jetting has been observed through cells in vitro [10], our previous findings, however, indicate that microbubble jetting behaviour does not play an important role in penetrating cell membranes [6]. However, the collapse of bubbles has been associated with the formation of free radicals [11].

3 EXPERIMENTS

To test, whether we could create inertial cavitation conditions under laboratory conditions at voltages similar to in-field equipment, we built three undamped ultrasound transducers with centre transmit frequencies between 200 kHz and 2.5 MHz (*cf.* Figure 1).

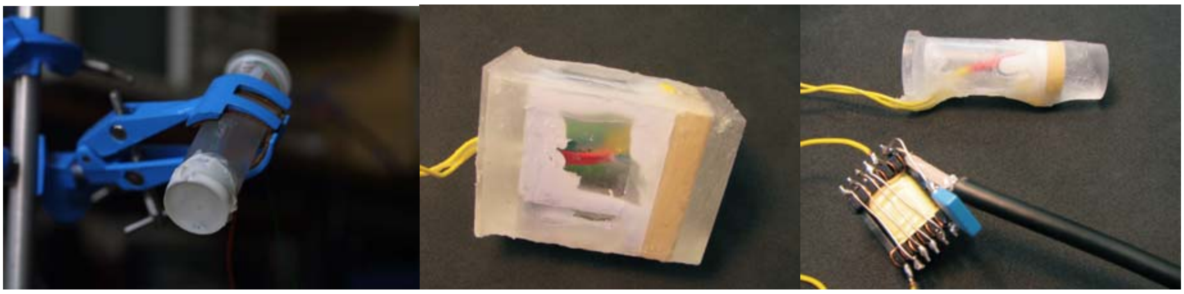

Figure 1: Three undamped ultrasound transducers with centre transmit frequencies between 200 kHz and 2.5 MHz.

These were inserted into a tank containing oversaturated water and subjected to quasi-continuous 5 V peak-to-peak AC signal at their centre transmit frequencies. The sound fields were measured with a broad-band hydrophone. In the acoustic focus, the highest sound pressure measured was 68 kPa at 2.2 MHz, i.e., MI < 0.05 << 0.3.

Clearly, these values are much lower than the cavitation thresholds from (2). Comparing the acoustic output of our transducers to the NATO Undersea Research Centre Human Diver and Marine Mammal Risk Mitigation Rules and Procedures, *i.e.*, 708 Pa between 31.5 kHz and 250 kHz, we find that at very close distance, the threshold for safe diving is surpassed.
Taking into account the double-distance sound pressure level and the low attenuation in water [13], this implies that even at these low voltages, the safe swimming distance is at least several meters away from the sound source.

4 CONCLUSION

Although the worst-case mechanical index close to our transducers is MI << 0.3, some of the acoustic pressures determined are higher than those allowable by the NATO Undersea Research Centre Human Diver and Marine Mammal Risk Mitigation Rules and Procedures.

5 REFERENCES

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