Focal Pressure Variations in Shock Wave Therapies Caused by Cavitation Bubbles

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Introduction

For medical applications of pressure pulses in extracorporeal shock wave therapies different generator types (electrohydraulic, electromagnetic, piezoelectric) are used. Unlike electrohydraulic sources, electromagnetic and piezoelectric transducers are characterised by a high reproducibility of the pressure pulse waveform. But even for these sources pressure measurements with a fiber optic probe hydrophone show significant variations in pressure waveforms after the first tensile phase of the wave. It is supposed that these quasi statistical changes are caused by the activity of cavitation bubbles. In this paper experimental and numerical investigations are presented which support this hypothesis.

Experiments

Experimental investigations were performed with a piezoelectric transducer used for orthopedic shock wave applications which is coupled to a water tank. Figure 1 shows the experimental setup. In Fig. 2 five measurements of

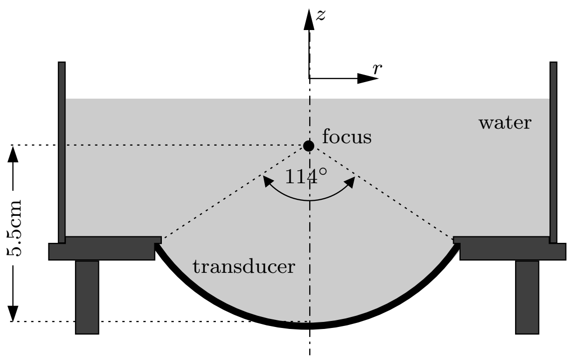

Figure 1: Experimental setup

the pressure signal at the acoustical focus are presented. For these measurements degassed water was used (oxygen content 1.5 mg/ℓ). The signals were recorded back-to-back with an intermediate time of 30s between the measurements and demonstrate the high reproducibility of the positive peak pressure and the first positive part of the waveform. But there are also significant variations in pressure waveforms approximately starting at the maximum tensile part of the signal. The driving voltage of the transducer is very stable and considering travel distance, influences of reflections from the hydrophone support can also be excluded. Therefore it is supposed that these variations in pressure waveform are caused by propagation effects and in particular by cavitation bubble activity. To confirm these hypothesis experimentally, cavitation effects have to be further reduced by using the degassed water and adding 3% acetic acid (per volume).

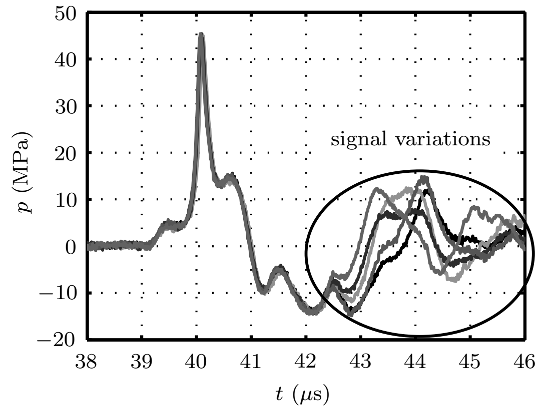

Figure 2: Focal pressure signals in degassed water

This is a proven method [1] to considerably reduce the number of cavitation nuclei by dissolving calcite particles in water. The acetic acid was added and after a waiting time of about 15 hours the focal pressure measurements were repeated. Figure 3 again shows five different focal

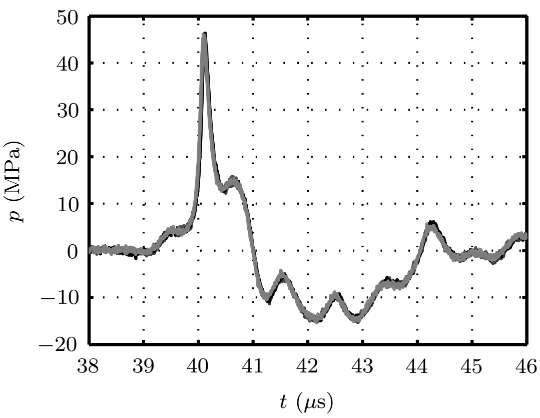

Figure 3: Focal pressure signals in degassed water + 3% acetic acid

pressure signals for the solution of water and acetic acid as propagation medium. The pressure signals are nearly identical, no more significant variations in the waveforms occur. This supports the above made hypothesis. On the other hand, if tap water (oxygen content 6.3 mg/ℓ) is used instead of degassed water more secondary oscillations and a further reduction of the tensile part of the wave are expected. In Fig. 4 averaged signals over 10 measurements for the three different water conditions, respectively, are presented. These experimental results demonstrate, that with increasing number of gas bub-

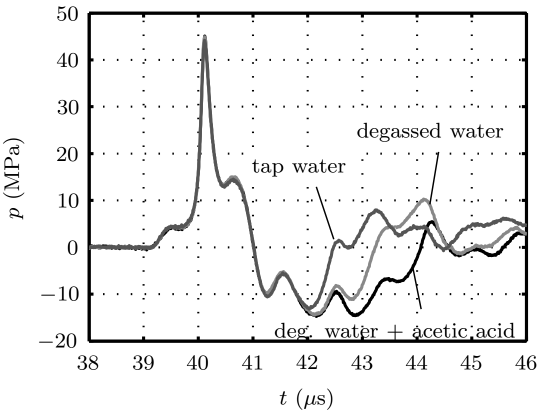

Figure 4: Averaged focal pressure signals for different gas content of the water

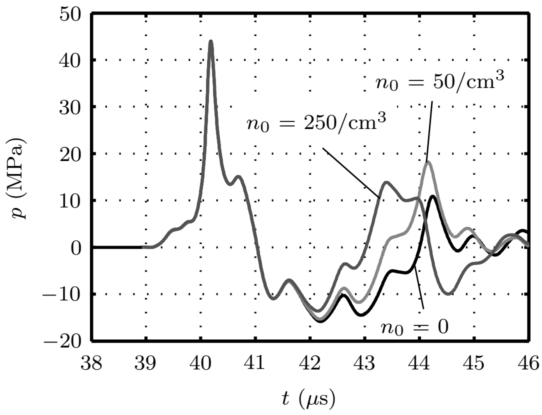

Figure 5: Simulated focal pressure signals for different initial bubble number densities

bles the tensile part of a shock wave gets truncated and is followed by augmented pressure oscillations. For a better understanding of the real mechanism of this effect, simulations were performed.

Simulations

A continuum model based on effective equations for the propagation of nonlinear pressure waves in a bubbly liquid is used for simulations [2]. The bubbly mixture can be treated as a continuum fluid when the size of the bubbles and the inter-bubble distance are small compared to the typical length scale of the wave process in the mixture. Furthermore a dilute mixture is assumed, which means that the local number of bubbles per unit volume remains small and therefore direct bubble-bubble interactions can be neglected. To account for the effects of relative motion between bubbles and liquid the conservation equations for mass and momentum are solved for both phases, the gas and the liquid. The dynamics of the radial bubble motion is calculated by the Gilmore equation [3], which includes the effects of liquid compressibility. Further basic assumptions for modeling the bubble behaviour are that the bubbles retain their spherical shape, a fixed amount of noncondensable gas is inside the bubble, which is compressed or expanded isothermally and effects of mass or heat diffusion are neglected. For the numerical implementation of nonlinear ultrasound propagation in the bubbly mixture, a two-dimensional explicit FDTD algorithm in cylindrical coordinates is chosen, assuming axisymmetry. A detailed description of the numerical treatment is given in [4]. The Gilmore equation is solved numerically using an explicit fifth-order Runge-Kutta scheme with adaptive time steps.

For the calculations the following parameters were used: uniformly distributed bubbles with an equilibrium radius of $R_0 = 3\,\mu$m and three different initial bubble number densities $n_0 = 0$ (no bubbles), $n_0 = 50\,/\text{cm}^3$ and $n_0 = 250\,/\text{cm}^3$. In Fig. 5 the simulation results for the focal pressures are plotted. The calculations confirm the experimental results. With increasing bubble number density the tensile part gets shorter and is followed by noticeable secondary oscillations. Analysing the simulation data reveals that this is mainly caused by a different propagation of the diffraction wave from the transducers edge as it passes through the expanding bubbles.

Conclusions

Experimental and numerical investigations were presented demonstrating that even for the propagation of a single shock wave the focal pressure waveform is influenced by the activity of cavitation bubbles. This provides new insights into the complex interactions between shock waves and cavitation bubble dynamics.

Acknowledgments

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References

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