Thermal Effects of Sawtooth Waveform HIFU in Tissue Phantoms

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Effect of acoustic nonlinearity of biological tissue results in ultrasound waveform distortion and, for high level of acoustic pressure, in formation of shock fronts. This effect may be strongly pronounced for high intensity focused ultrasound (HIFU). When the sawtooth waveform is developed at the focus, the corresponding absorption rate increases. This can be used in therapeutic applications of HIFU, such as focused surgery and hemostasis, when it is desirable to achieve localized elevated absorption. Nonlinear enhancement of heating is studied experimentally and theoretically in tissue phantom for 1.1 MHz piezoceramic sources of 10 cm diameter 20 cm focal length. Continuous ultrasound wave and repetitive tone bursts of the same mean power are employed to study the effect of the nonlinearity on temperature rise in gelatin. The experimental data are compared with the results of numerical modeling of the temperature field. The theory is based on the KZK-type equation for the acoustic field combined with the Bio-Heat equation for the temperature. A significant increase of temperature rise was predicted and observed for 1000 W/cm^2 peak intensities due to the excess absorption at the shocks.

INTRODUCTION

It is a classical effect of nonlinear acoustics that intense sound wave propagating in nonlinear medium is distorted because waveform portions with higher pressures propagate faster than those with lower pressures. This results in waveform steepening and formation of shock fronts. The effect may be strongly pronounced for high intensity focused ultrasound (HIFU) used in focused surgery and hemostasis. As the acoustic wave approaches the focus, it becomes strongly nonlinear, shock fronts develop, i.e. initially sinusoidal waveform reshapes to a sawtooth profile.

The shock fronts imply the existence of many higher harmonics in the propagating wave. Since the sound absorption in tissue is strongly dependent on the frequency, the wave energy absorption increases near the focus. Choosing focusing geometry and source parameters can control this excess absorption and corresponding tissue heating. It is possible therefore to take advantage of the acoustic nonlinearity in producing thermal effects only at the focus, and not in the intervening tissue. The goal of this paper is to demonstrate experimentally and theoretically the possibility of using nonlinear effects to achieve controlled elevated absorption of HIFU.
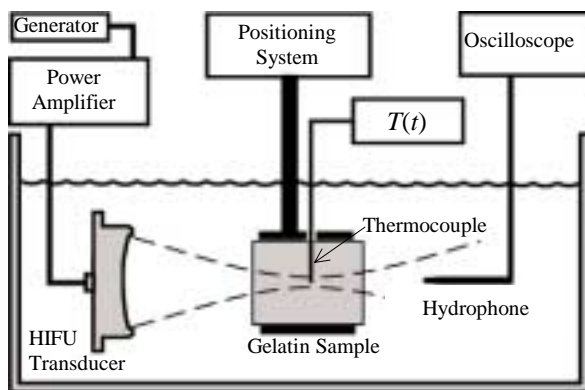
EXPERIMENT

Experiment was performed with tissue phantom made from 12% concentration gelatin. The set-up is shown in the Fig.1. The gelatin sample had a cylindrical shape of 115 mm length and 90 mm diameter. It was attached to positioning system (Velmex, USA). A 0.3 mm diameter thermocouple wire was embedded into the middle of the sample, the temperature was recorded every 1 second with an accuracy of 0.1 K (Digi-Sense, Cole-Parmer Instr. Co., USA). Focused ultrasound beam was radiated by a transducer made from PZT spherical cap with a resonance frequency of 1.1 MHz, aperture diameter of 100 mm, and radius of curvature (focal length) of 200 mm. The PZT element

FIGURE 1. Experimental set-up

was mounted in a stainless steel housing and was air-backed. The transducer was excited in c.w. or pulse regime from RF power amplifier (A-300, ENI, USA). The thermocouple was positioned at the focus of the HIFU source. For precise positioning of the thermocouple on the acoustic axis, the source was excited at its third harmonic (3.3 MHz) and the transmitted signal was measured by a needle hydrophone (SEA, USA) for various lateral positions of the gelatin sample. The corresponding 2D distribution of the hydrophone signal represented an acoustic shadow of the thermocouple wire; the sample was then shifted to the position corresponding to the tip of the shade. To study the effect of acoustic nonlinearity, in two different measurements the transducer was driven by 1.1 MHz signal of the same mean power but different envelope: (1) continuous wave and (2) repetitive tone bursts of 1kHz repetition frequency and 9% duty cycle. In linear medium these regimes would result in the same heating effect proportional to the mean power. On the contrary, in nonlinear medium one would expect more heating at higher peak intensity, i.e. in pulse regime. Mean power was measured using radiation force balance method [1]. Temperature measurements were performed at mean acoustic power of 11.5 W.
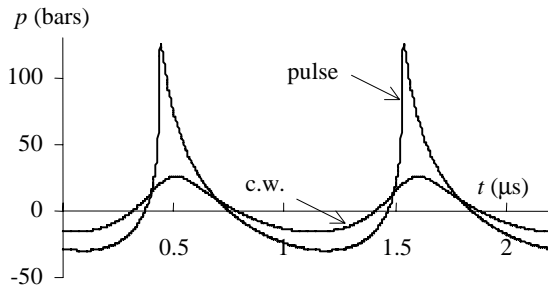
THEORETICAL MODELING

The theory was based on the KZK-type equation for the acoustic pressure field p:

$$\frac{\partial}{\partial \tau}\left(\frac{\partial p}{\partial z} - \frac{\beta}{\rho c^3} p \frac{\partial p}{\partial \tau} - \frac{b}{2\rho c^3}\frac{\partial^2 p}{\partial \tau^2}\right) = \frac{c}{2}\Delta_\perp p \, ,$$
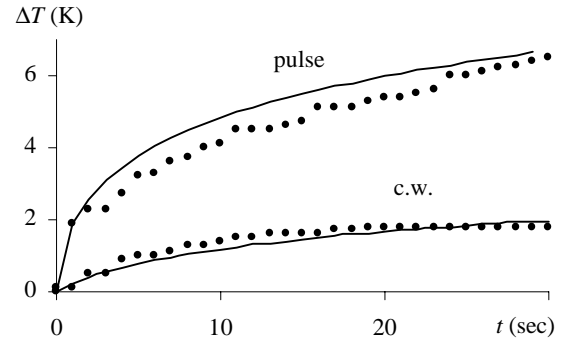
combined with the thermoconductivity equation for the temperature T:

$$\rho C_p \frac{\partial T}{\partial t} = \kappa \Delta T + \dot{Q} \, .$$

Here $\tau = t - z/c$ is retarded time, c is speed of sound,

FIGURE 2. Waveform at focus in c.w. and pulse regime (modeling)

FIGURE 3. Temperature rise at focus in c.w. and pulse regimes of the same acoustic power: Experiment (circles) and theory (solid lines)

z is axial coordinate, β is coefficient of acoustic nonlinearity, ρ is density, b is viscousity coefficient, $\Delta_\perp$ is transversal Laplasian, C_p is specific heat, κ is thermoconductivity coefficient, and $\dot{Q}$ is heating rate due to sound absorption. Details of the numerical simulation can be found elsewhere [2, 3].

RESULTS

Predicted waveforms at focus are shown in Fig.2. Note the steepening of the wavefront — a measure of the effect of nonlinearity. Shocked waveform in pulse regime would have very strong absorption at the focus. Fig.3 represents experimental and numerical results for temperature increase at focus as a function of HIFU exposure time. It is seen that pulse regime provides more efficient heating.

ACKNOWLEDGEMENTS

REFERENCES

1. Yu.A. Pishchalnikov, O.A. Sapozhnikov, and T.V. Sinilo, Acoustical Physics, **48**(1), 2002 (in print).
2. F.P. Curra, P.D. Mourad, V.A. Khokhlova, R.O. Cleveland, and L.A. Crum, IEEE UFFC, **47**, 1077-1089 (2000).
3. E.A.Filonenko, V.A.Khokhlova, Acoustical Physics, **47**(4) (2001)