Numerical Characterization of Laser-Generated Focused Ultrasound Pulses

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Background, motivation and objective:

Laser-generated focused ultrasound (LGFU) systems using an optoacoustic lens, which converts an incident pulsed laser beam into a powerful ultrasonic pulse, have been actively developed. LGFU could be applied to various micro-ultrasonic treatments such as cell detachment, drug delivery, and lithotripsy. It is important to determine suitable transducer characteristics in terms of focal spot dimension, center frequency, bandwidth, and peak pressure amplitude at the focus. To evaluate and predict these properties, temporal and spatial acoustic profiles should be acquired numerically as well as experimentally. We develop a numerical method to predict original LGFU waveforms excluding detector bandwidth effects. We demonstrate that LGFU evolution from the transmitter surface to the focus includes shock formation and edge wave-induced distortion, both of which play crucial roles to determine frequency and amplitude characteristics at the focal zone.

Statement of contribution/method:

We constructed a thermo-acoustics model including the laser beam profile as a thermo-acoustic source. In this model, an energy conversion equation was used for generating acoustic waves by thermal expansion. Both momentum conversion and continuity equations were used for propagation of acoustic waves. For simulation, we used a software tool (COMSOL Multiphysics Version 5.4). The nonlinear effect was taken into account, which appears prominently with a high acoustic pressure, and a high operating frequency. Thus, we separated our model into two regimes: linear and nonlinear. The Westervelt equation was used for nonlinear propagation model where a strong amplitude pressure is applied. The simulated waveforms along the focused ultrasound path were confirmed with experimental waveforms generated by carbon nanotube (CNT)-polydimethylsiloxane (PDMS)-based lenses. We fabricated a lens by preparing a 0.5 mm thick CNT-PDMS layer that is coated on a glass substrate.

Results/Discussion:

For both theoretical and experimental cases, we demonstrated that the edge wave emanating from the outer rim of lens is combined with the wave generated from the central zone of lens as it propagates towards the focal point. Initially near the lens surface, the edge wave is clearly separated and gradually mixed with the main wave with propagation, which eventually produces a bi-polar waveform of LGFU at focus. This suggests that our modelling is useful to predict negative pressure amplitudes at focus capable of inducing acoustic cavitation and thus performing tissue therapy. Moreover, our calculation results were compared with experimental ones in terms of focal spot dimensions and frequency characteristics. The nonlinear effect was confirmed as shock formation for both numerical and experimental results. For both linear and nonlinear regimes, we discuss geometrical factors and input laser beam profiles providing shock formation, edge wave-induced distortion, and negative peak formation.