Robust and miniaturized optoacoustic lenses with high damage threshold for pulsed cavitational therapy

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Background, Motivation and Objective

Various light-absorbing materials have been used as optoacoustic ultrasound transmitters. Among them, carbon-nanotube (CNT)-polydimethylsiloxane (PDMS) composite films are known as highly efficient and robust optoacoustic transmitters. Previously, a chemical vapor deposition (CVD) process to grow CNTs and fabricate CNT-PDMS films only guaranteed extraordinary robustness (several hundreds mJ/cm^2). However, the CVD-based fabrication has limitations in spatial uniformity of CNT, process yield, and device dimension. Other optoacoustic transmitters employing CNT-gel, candle soot nanopaticles and Cr had low damage threshold laser energies, resulting in a limited pressure output.

Here, we introduce a new approach to fabricate CNT-PDMS composite film by spraying a CNT solution onto an unpolymerized PDMS film. This ensures spatially spread distribution of CNT in PDMS without agglomeration, resulting in a well-mixed CNT-PDMS composite, which is confirmed by scanning-electron microscopy. Thus, CNT-PDMS composite films exhibit great robustness against laser-induced damage (>300 mJ/cm^2), thus enabling significant enhancement in the maximum-available pressure output. We demonstrate a laser-generated focused ultrasound (LGFU) system with a miniature optoacoustic lens (<6 mm) that produces unprecedently high-output pressure amplitudes in such dimension. This enables us to produce pronounced shock and free-boundary cavitation that can disrupt blood clots ex vivo.

Statement of Contribution/Methods

CNT-PDMS composite optoacoustic transmitters were fabricated by using a spray-based method. We characterized the damage threshold laser energy of these transmitters using nanosecond-pulsed laser beams. Then, we fabricated miniature LGFU lenses (<6 mm in diameter) and demonstrated mechanical disruption of blood clots ex vivo. The LGFU performance is characterized in terms of pressure output at focus, shock formation, focal gain, geometrical profile, threshold laser energy for free-boundary cavitation, and blood clot fragmentation capability under various input laser energies.

Results/Discussion

The laser-induced damage threshold of the proposed transmitter was measured as high as 312 mJ/cm^2, which is 3~10-fold higher than those of other transmitters based on CNT-gel, candle soot nanopaticles and Cr. As we achieved the maximum-input laser energy enhancement by 3~10 fold, the maximum-pressure output was also increased for a given transmitter dimension. Using the small aperture lens with the diameter of 6 mm and the damage threshold of 158 mJ/cm^2, we could even produce free-boundary cavitation firstly in this work, which requires the pulsed laser energy of only 8.1 mJ. Such enhanced optoacoustic output enabled our miniature lens to disrupt blood clots ex vivo with microscale precision (<100 µm). We expect that our approach can be used to construct miniaturized LGFU systems for integration with endoscopic probes.