Numerical simulations of the ultrasonic tissue ablation process

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Ultrasonic tissue ablation is based on rapidly (<3s) raising the temperature in a small volume (around 13mm^3) of tissue by a single exposure to a beam of high-intensity focused ultrasound (HIFU). The process does not thermally destroy tissue outside the focus of the beam. Thermal ablation of a larger volume of tissue (e.g. a tumor) requires the planning and execution of multiple individual exposures of the tissue to the HIFU beam so that the entire volume intended for thermal destruction is covered by the necrosis. HIFU has been used in clinical practice for the thermal destruction of various solid tumors (e.g. prostate, breast, liver, and uterine fibroids) [1]. Predicting the location and extent of planned thermal ablation of tissue will ensure treatment efficacy and safety. The aim of this study was to create a theoretical tool for predicting the location and the volume of the necrosis developed inside the *ex vivo* tissue as a result of its exposure to the pulsed HIFU beam using the ultrasound imaging-guided HIFU ablation system [2] for different duty cycle values.

The proposed model is based on a numerical simulation of non-linear propagation of acoustic waves and heat transfer in heterogeneous media using a k-wave toolbox [3]. The wave propagation equations were solved in a box of the size 7cm x 7cm x 10cm. The source of acoustic waves (bowl-shaped HIFU transducer with a diameter of 64 mm and focal length of 62.6mm simulating the one used in real experiments [2]) was located at the border of the region and directed along with the longest size of the simulation box. The frequency of the transmitted wave was 1.08MHz. Numerical discretization allowed to simulate propagation taking into account frequencies up to 6.48MHz, (6 harmonics could be included). The distribution of heat sources in the simulated two-layered structure (water (50mm) - tissue (40mm)), based on the calculated acoustic pressure distribution of the propagating wave, was determined. Additionally, the temperature distribution after a 3-second exposure of the medium to the HIFU beam for three duty cycle values and the cooling curves at 120s were computed. This allowed to calculate the thermal dose received by the simulated tissue and to determine from this the size of the necrosis formed.

Experimental results from previous studies and the results of simulations were compared. The difference between the length of the simulated necrotic lesion and the experimental necrotic lesion was less than 0.5 mm on average, as did the difference between the diameter of the simulated and experimental necrotic lesions. The ablation volumes obtained showed a 90% agreement between the simulation and experimental results on average.

The consistency of numerical simulation and experimental results is sufficient to proceed with further studies aimed at numerical optimization of the temporal and spatial thermal ablation of larger tissue volumes.

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References:
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