A numerical algorithm for reducing the time of HIFU thermal ablation of large tissue volumes and its experimental verification

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The standard HIFU (High Intensity Focused Ultrasound) thermal ablation procedure of large tissue volumes requires multiple sonications and a constant long cooling time, usually about 60 seconds [1] between successive sonications, which significantly prolongs the ablation process. Therefore, the objective of this study was to develop a numerical algorithm to shorten HIFU ablation time that can be applied to any spatial scanning plan. Numerically generated procedures for large-volume ablation have been verified experimentally on ex vivo samples.

The developed algorithm consists in calculating using the k-wave toolbox the space-time distribution of sound pressure in the pulsed beam generated by the HIFU transducer and propagated in the two-layer system of water-tissue media, and then determining the power density of the heat sources and the evolution of the thermal field using the pseudo-spectral k- space method. Based on the calculated spatial-temporal distribution of temperature at a given time step, the spatial distribution of thermal dose in the assumed system is calculated. According to these distributions, assuming the threshold of irreversible thermal damage to the tissue CEM43 = 240 min and the maximum allowable temperature in the system during sonication (60°C), the beam duty cycle was selected, thus creating a numerical proportional controller used in HIFU thermal ablation. The algorithm outputs for a given spatial plan of ablation, the adjusted values of the duty cycle at a given moment of time, the moment of transition to the next sonication target, and the predicted spatial distribution of the necrotic lesion being formed. The calculated size of necrotic changes was experimentally verified.

Two cylinders with diameters of 5 mm and 9 mm and a height of about 10 mm, for which the standard procedure consisting of 3 s of sonication and 60 s of cooling takes 8.45 min and 30.5 min, respectively, were scheduled for ablation using a reduced-time algorithm. The developed algorithm reduced the time of the mentioned ablation procedures to 1.17 min and 2.98 min, so to about 13.8% and 9.7% of the time of the standard procedure. The average difference in length and diameter between experimentally and numerically obtained necrotic lesions using the developed algorithm was 1.7 mm and 0.6 mm, respectively.
The developed algorithm made it possible to shorten the ablation time by about 7 times and 11 times, respectively, and to predict with good accuracy the size of the expected necrotic lesion, so it has the potential to be applied in clinical practice in the future.

References:
[1] Experimental evaluation of the near-field and far-field heating of focused ultrasound using the thermal dose concept. Ultrasonics. 2021;116:106513.