Experimental comparison ex vivo of different sonication patterns for volumetric MRgHIFU ablation

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Introduction. Existing peer-reviewed publications on clinical studies with MR-guided focused ultrasound surgery used the point-by-point sonication method. One elementary sonication is performed for 12-20 seconds at a given location, ablating ellipsoidal shaped 0.2-0.4 mL volume of tissue, and afterwards 30-90 seconds cooling period is allowed. Oncologic quality of ablation is defined here as uniform tridimensional ablation of a large volume including not only the malignant tumor itself, but also 5 to 10 mm margin, such as every cancer cell is destroyed. Alternatively to “point-by-point” technique, literature studies describe the so called “volumetric” sweeping (1,2), based on three principles: 1. the HIFU transducer is continuously active [duty cycle near to 100%] while the focal point describes its trajectory; 2. the heat diffusion in tissue is exploited to homogenize the thermal buildup, i.e. generating uniform temperature elevation in the target region, and 3. the temperature elevation on the border of the heated region prevents the central zone to cool down (”oven effect”). These three principles enable fast and uniform ablation of oncologic quality. To investigate different sonication patterns, in the presented work we performed fast switched foci (i.e. interleaved) volumetric sonication using a phased array transducer coupled to a 2D mechanical positioning system.

Methods. An MR compatible randomized HIFU transducer (256 elements, F=974 kHz, spherical shape, radius 130 mm, aperture 140 mm, element diameter 6.6 mm, from Imasonic, France) was driven by a 256 channels generator and positioned by a 2D mechanical system XZ (both from Image Guided Therapy, France). In house written software package was used for on line treatment planning and hardware control. PRFS MR-thermometry (3) was used for accurate on line monitoring of temperature elevation in 5 slices (1 sagittal + 1 transverse aligned each with the beam axis and 3 coronal) acquired interleaved in 3.8 s on a 3T whole body MRI scanner (Magnetom Trio @ Tim system, Siemens AG, Germany). A GRE-EPI sequence was used with echo train length 9, TE = 8.9 ms , TR=161 ms, FA 10°, BW= 500Hz/pixel, voxel 1x1x5 mm^3, 40 to 60 dynamic scans, 0.2 to 0.4ºC STD. Different sonication patterns prescribed in the treatment plane (orthogonal to the main axis beam) were compared experimentally on *ex vivo* Turkey muscle (degassed for 30 min under vacuum): line scan, unitary circle and concentric multi-circle disk (4). The applied power was automatically compensated based on pre-calibration look up table, such as the actual focal point intensity was invariant within the same pattern, whatever the steering. Following comparisons were performed: 1. line scan versus circular trajectory with length and respective diameter of 4, 8, 12, 16 and 20 mm. The reference acoustic power when focusing on the symmetry axis was set to 100 W_{ac}, 2. line scan versus disk (i.e. concentric multi-circle) with the length of the linear segment equal to the outer circle diameter. The reference acoustic power was 133 W_{ac}. In each comparison couple, both patterns were implemented with the same number of discrete foci and were sonicated for the same duration (set to 5·pattern_size[mm] sec).

Results and Discussion. Temperature maps are shown in 2 orthogonal planes at the end of the sonication process for two comparison-couples. Figure 1 illustrates the temperature elevation after a line scan of 16 mm length (a-c) and a circle trajectory of 16 mm diameter (d-f). The maximum temperature elevation was 12ºC respectively 8ºC. The temperature maps obtained for a 24-mm length line scan and respectively a 20-mm disk (5 concentric circles with diameters of 4, 8, 12, 16, 20 mm) are illustrated in Figure 2. For this case, the central temperature elevation was approximately 17ºC for both patterns. The temperature profile taken along the transducer symmetry axis (c and f for both figures) shows clearly for circular patterns the tendency of the maximum temperature to drift towards the transducer (3 to 12 mm drift, proportional to the diameter), whereas the thermal build up remained longitudinally symmetrical for line scans even at 24 mm size. The maximum temperature reached for circular trajectories was always inferior compared to line scans. For concentric multi-circle patterns the drift of the thermal pattern towards the transducer was also clearly observed both on temperature and thermal dose maps that was equal to approx. 30% of the outer circle diameter. We used rather low frequency HIFU (974 kHz) but with higher sonication frequency this situation is expected to get worst because of enhanced absorption in tissue.

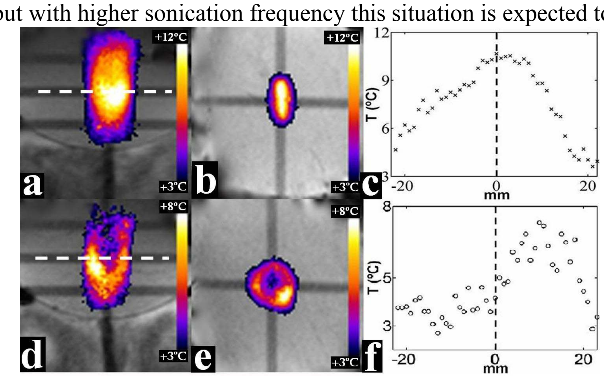

Figure 1. Temperature maps in axial (**a**,**d**) and coronal (**b**,**e**) planes at the end of sonication along linear (**a-c**, 16 mm length) and circular (**d-f**, 16 mm diameter) trajectories. Shown FOV is 80 mm. Figures c and f illustrates the temperature profile along the transducer symmetry axis. Zero coordinate stands for the prescribed treatment plane. Positive direction points towards the near field.

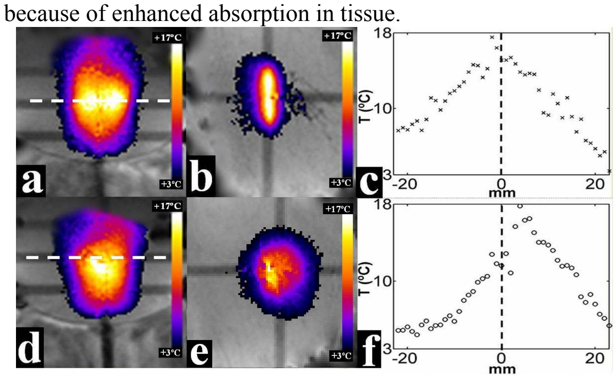

Figure 2. Temperature maps in axial (**a**,**d**) and coronal (**b**,**e**) planes at the end of sonication process along a trajectory describing a line (**a-c**, 24 mm length), and 5 concentrically circles (**d-f**). Shown FOV is 80 mm. Figures c and f illustrates the temperature profile along the transducer symmetry axis. Zero coordinate stands for the prescribed treatment plane. Positive direction points towards the near field.

Conclusion. Disk patterns showed no advantages over line scan sonication in term of ablation speed (mL/kJ) nor in term of temperature uniformity, but leaded to size-dependent and tissue absorption-dependent shift of the thermal build up towards the near field. Combinations of parallel lines trajectories appear more suitable for complex treatments. Standardization of therapeutic procedure may be required to guarantee safe ablation.

References. 1. Salomir R, Palussiere J, Vimeux FC *et al*. J Magn Res. Imaging 2000; 12:571-583. 2. Palussiere J, Salomir R, Le Bail B *et al*. Magn Reson Med. 2003; 49:89-98. 3. Ishihara Y et al. Magn Res Med 1995;34(6):814-823. 4. Köhler MO et al, Phys Med, 2009 36(8):3521-35.