MRI-guided Focused Ultrasound applied with Continuous Sonication Produces Predictible and Reproducible Thermal Lesion

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Objective. To demonstrate that MRI-guided focused ultrasound applied with continuous sonication within a circular or elliptical ROI produces a predictable and reproducible thermal lesion.

Introduction. Focused ultrasound allows non-invasive deposition of heat inside the body. This technology has been successfully applied for thermal ablation of tumors. Initial studies were based on the single-point-sonication technique (1). The treatment duration is reduced significantly with the focal point displacement along spiral trajectories under continuous sonication (2). In addition, the last method has the advantage to deliver a uniform thermal dose within the selected volume. However, the question of the thermal safety in neighbouring tissue must be addressed, since the lesion shape and size is determined by the accumulation of repeatedly overlapped low-intensity, spatially smooth acoustic fields.

Materials and Methods. In this study, two mathematical models were used to predict the thermal lesion. The first model neglected the heat diffusion in tissue and approximated the acoustic field by a spherical wave front, propagating only inside the aperture cone. The second model consisted of a complete 3D numerical simulation of the acoustic field of the transducer, in combination with the bio-heat transfer equation. Simulated temperature data sets were compared to experimental PRF-MR-temperature maps. The predicted shape and size of the thermal lesion were compared to the in-vivo post-treatment Gd-enhanced MR images.

Experiments were performed on a 1.5T Philips clinical MR-scanner equipped with an MR compatible 14-ring spherical ultrasound transducer integrated in the bed of the MR system (Imasonic, Besancon, France, f = 1.5 MHz, D = 96 mm, R = 80 mm, aperture number D/2R=0.6). The ultrasound probe can be hydraulically moved in the horizontal plane with an isotropic spatial resolution of 0.25 mm. Maximum acoustical power was 70W. In-vivo experiments were performed on the left thigh of twelve white New Zealand female rabbits (weight 3-3.5 kg). Real-time PRF based MR-thermometry was performed using fast 3D or 2D-multislice gradient echo sequences with following parameters: a) 3D: FOV=128 x 128 x 60 mm, acquisition 128 x 78 x 12, reconstruction 128 x 128 x 12, TR = 50ms, TE = 15 ms, 13 k-space lines /TR, flip angle 20°, 3.6 sec per volume and b) 2D multi-slice : FOV=128 x 128 mm, 7 slices of 6 mm thickness, acquisition 128 x 90, reconstruction 128 x 128, TR = 80ms, TE = 18ms, 15 k-space lines /TR, flip angle 30°, 5.12 sec per volume. MR phase maps were on-line transferred to a PC-workstation, that was also running the software to control the FUS transducer. Elliptical regions of different size and aspect ratio were repeatedly covered with 5 to 10 successive inside-out spiral trajectories, calculated as in ref(2), see Figure 2 (top-left corner). Sampling time was 1.6 sec per sonication point. Six different shape of ellipses were considered, corresponding to ellipse axes (a,b) equal to respectively (11,11) mm, (11,15) mm, (11,19) mm, (15, 15) mm, (15,19) mm, (19,19) mm. For each type of trajectory two animals were employed. The temperature was automatically controlled and stabilized to 50°C during 10 to 20 minutes. MRI follow-up was performed at 3 and 10 days post-treatment (Gd-enhanced images).

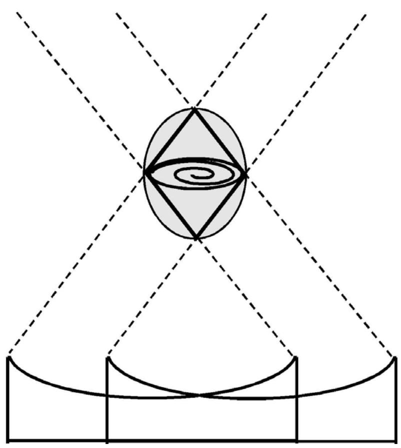

Figure 1. A simple geometrical model for the accumulation of thermal build-up during the continuous sonication.

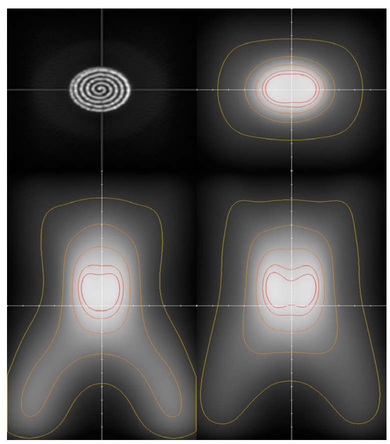

Figure 2. 3D simulation of the temperature Increase at the end of the trajectory. Three orthogonal planes are shown.

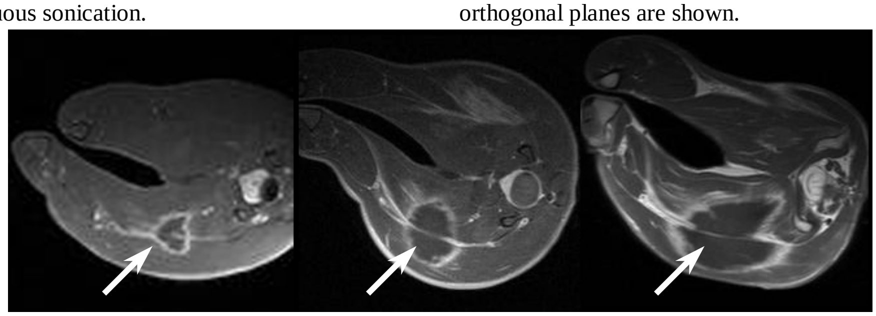

Figure 3. Gd-uptake images at 4 days post-treatment, for spiral trajectories of 11, 15 and 19 mm diameter, respectively. Note that some distortion of soft tissue depending on the animal position during the follow-up scan could not be avoided.

Results and Discussion. The theoretical results indicated that the accumulation effect of the acoustic field yield to a thermal build-up ellipsoidally shaped (Fig 1 and 2). The transverse section in the thermal ellipsoid corresponded to the initial ellipse covered by the focal point trajectory. The longitudinal diameter of the ellipsoid was equal to the short diameter of the ellipse, divided by the aperture number of the FUS transducer. Post-treatment MR-follow-up data confirmed the theoretical prediction (Fig 3). The lesion size exceeded 1 to 8 mm the extention of the ellipse because of the heat diffusion during the treatment. This effect was more important for larger ROI, due to the increasing treatment time.

Conclusion. The lesion size and shape were predictable and reproducible when the FUS transducer was operated under continuous sonication and when the temperature increase in the target ROI is stabilized to approximately 50°C. This treatment is potentially suitable for efficient and uniform destruction of malignant tumors.

References

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2. Palussière J et al, MRM 49: 89-98 (2003)