MRI-based temperature analysis of transcranial MRI-guided focused ultrasound surgery for functional neurosurgery

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Introduction: Previously, initial findings in three glioma patients treated with a transcranial MRI-guided focused ultrasound (TcMRgFUS) system were described[1,2]. This system uses acoustic models, geometric and density information derived from CT scans, and a phased array transducer to correct for skull-induced aberrations of the ultrasound beam to enable noninvasive thermal ablation in the brain without overheating the skull[3,4]. Here we report on MRI-based temperature analysis obtained in treatments in a larger patient group with an upgraded version of the system to further characterize its safety profile with respect to skull heating.

Methods: The treatments were approved by the local IRB and informed consent was obtained. Nine patients were treated with TcMRgFUS as part of a phase I clinical trial for neuropathic pain[5]. The TcMRgFUS system tested was the ExAblate 4000 (InSightec, Haifa, Israel), which consists of a 30 cm diameter hemispherical 1024 element phased array transducer operating at 650 kHz coupled with a water cooling/circulation/degassing system and a clinical 3T MRI unit. Imaging was performed using an 8-chanel torso coil wrapped around the transducer. Before treatment, the patients' heads were shaved, immobilized using a stereotactic frame, and acoustically coupled to the transducer with chilled and degassed water. The treatments were performed fully awake. During treatment, the acoustic power was increased over several 10-20s sonications until focal heating was observed in MR temperature imaging (MRTI)[6] to verify the hotspot location within the target area in the Central Lateral Thalamus[5]. Then, the acoustic power was increased further over additional sonications to a level (~50-59°C) sufficient to produce thermal tissue ablations.

The maximum temperature rise achieved at each visible focal hotspot was calculated and compared to the heating on the outer brain surface induced by ultrasound absorption in the skull. To quantify this skull-induced heating, the hottest 5% of the voxels within 7 mm of the outer brain surface were identified on coronal and sagittal MRTI (average of 3 images at end of imaging). These regions were expanded by 1 voxel in each direction (to reduce noise effects), and the average temperature was found. This procedure was chosen to present a conservative estimate of skull-induced heating. In addition, the average heating on a 2 voxel wide strip at the brain surface was calculated. Maximal acoustic power per patient ranged from 570-1350W (max energy: 8.3-20.3 kJ). A total of 153 sonications were analyzed. Phase instabilities in MRTI were removed by fitting non-heated brain regions to a smooth surface and extrapolation[2].

Results: Focal heating was readily observed during every treatment (Fig. 1). The mean peak focal temperature achieved for the nine patients was 52.6 ± 2.9°C (range: 47.9-56.3°C). Average temperature measurements (normalized by acoustic power) over time at the focus and in hottest regions near the brain surface are shown in Fig 2 for all 20s sonications. The average ratio between focal heating to brain surface heating was 11.3 ± 6.3, using the conservative metric, and 28.2 ± 18.4 using the whole brain surface.

Discussion: The ratio between focal heating and skull-induced heating, a critical value in determining the safety profile of the system was approximately 2.7 times higher than in the previous study[2]. This improvement was presumably due in part to the manufacturer doubling the number of phased array elements in the transducer and improving the immobilization and image registration, which improved the transcranial focusing, and more robust temperature measurements with a 3T scanner and a phased array imaging coil, which allows for more precise placement of the imaging plane on the hotspot. These treatments were also performed in brain tissue, which may have been easier to heat than tumor due to local differences in acoustic properties and blood flow, and other factors resulting from a different patient population may have contributed. Overall, the results appear to increase the safety profile of the device, potentially allowing for an increased portion of the brain that can be targeted without overheating the skull bone.

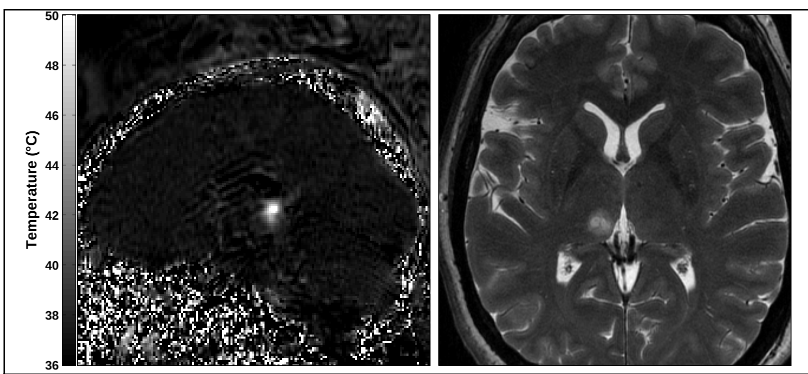

Fig 1. Sagittal MRTI and post-treatment T2-weighted FSE acquired during and after TcMRgFUS.

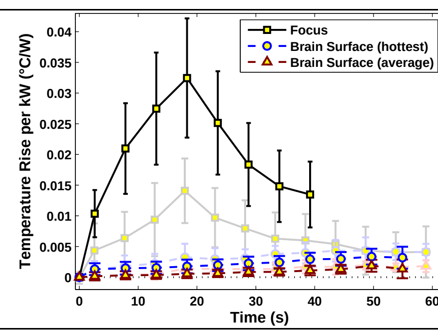

Fig 2. Average peak temperature rise per kW of acoustic power at the focus and on the brain surface for 20s sonications (N=81). The same result from previous study[3,4] is plotted in the background for reference.

References

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