MRI-monitoring of heating produced by ultrasound absorption in the skull: in vivo study in pigs

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Introduction: The purpose of this study was to test the use of MRI-derived thermal mapping to monitor the temperature rise on the brain surface and in the scalp induced by skull heating during ultrasound exposures in vivo. This work is in preparation for clinical tests of trans-cranial focused ultrasound surgery (1-3).

Methods: Eleven locations in three pigs were targeted with unfocused ultrasound exposures. The square, air-backed planar transducer was constructed from 1-3 piezocomposite material (square, 2cm wide, frequency: 690 kHz; acoustic power 8.2 - 16.5 W; duration: 20s). During the sonications and for four min afterwards, the temperature was monitored parallel to the beam direction with MRI thermometry (PRF technique (4), FSPGR sequence, parameters: TR/TE: 39.5/19.3 ms, flip angle: 30°, bandwidth: 3.57 kHz, FOV: 20 × 15 cm, slice thickness: 5 mm, 256×96 matrix, scan time: 4 s). In two pigs, a bare-wire copper-constantan thermocouple was inserted in the muscle adjacent to the skull. In those cases, the sonications were repeated both with and without MRI monitoring to avoid artifacts in the thermocouple measurements. Also, in two pigs, sonications were repeated post-mortem (5 sonications in 3 locations, no thermocouple). The average temperature rise as a function of time was calculated in a 1 × 7 voxel (0.8 × 5.5 × 5 mm^3) ROI in the muscle immediately outside the skull and another on the brain surface.

Results: The temperature distribution in the scalp and brain could be clearly seen in the temperature maps (Fig 1). The average peak temperature rise in vivo was 2.8 ± 0.6°C and 4.4 ± 1.4°C on the brain surface and scalp respectively at an acoustic power level of 10W (Fig 2). The scalp temperature agreed with that measured with a thermocouple probe inserted adjacent to the skull (average peak temperature 4.6 ± 1.0°C), although there was more variation in the measurements than in the brain, presumably due to artifacts induced by pulsatile blood flow. The temperature rise increased approximately 1°C during the post-mortem sonications, and the uncertainty of the measurements in the scalp was reduced, due to the lack of blood flow. The standard deviation of the noise in the temperature images (in not heated areas in the brain) was ±0.40°C in vivo and ±0.28°C post mortem. Characterization of the transducer showed that the average acoustic intensity was 1.3W/cm^2 at an acoustic power of 10W.

Discussion: Previously, we measured the focal temperature in rabbit brain in vivo when sonicating through an ex vivo human skull with a pre-clinical device operating at the same frequency (5). Those results, along with those found here, indicate that the temperature rise on the surface of the brain induced by skull heating will not limit the ability to perform ultrasound thermal ablation in the brain at 690 kHz when focusing through the skull, but that cooling of the head during the procedure may be necessary. The ability to monitor the temperature rise next to the skull with MRI-based thermometry as shown here will allow for safety monitoring during the procedure.

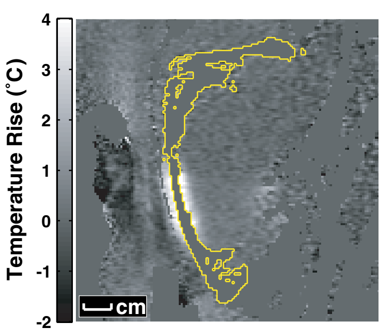

Figure 1: Sagittal temperature map acquired at peak temperature rise during a 10W sonication in the pig brain. The temperature rise was not visible in the skull (contour), due to the lack of MR signal.

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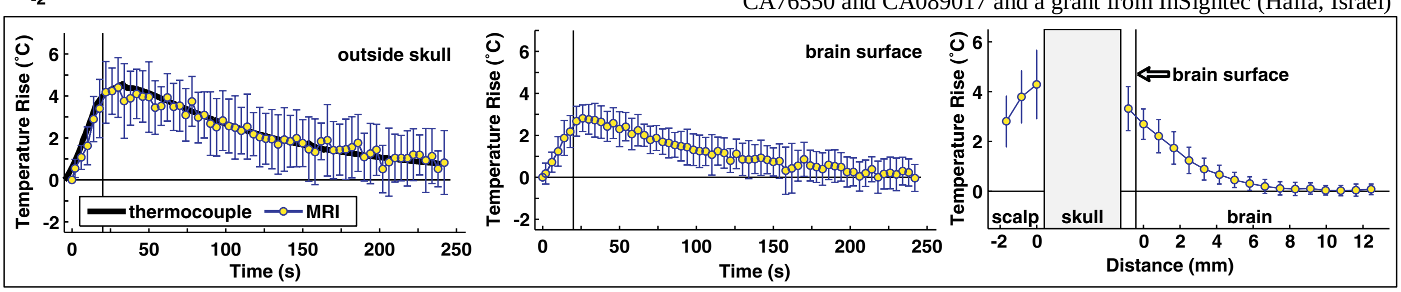

Figure 2: Plots of the average temperature rise (± SD) as a function of time on the brain surface and scalp during 20s sonications. For the averaging, the temperature rise for each individual sonication was scaled based on the acoustic power to that of a sonication at 10W. The solid line indicates the average of the measurements with the thermocouple (error bars not shown for clarity; average error bar 0.7 ± 0.2 °C).