MRI thermometry of near field cumulative heating induced by successive HIFU ablations

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Introduction

High Intensity Focused Ultrasound (HIFU) under MR guidance has been shown to be an efficient form of tumor treatment, especially for symptomatic uterine fibroids. A risk associated with this method is excessive near-field heating, which in extreme cases may result in skin burns if the heating is not noticed. The improved monitoring capabilities provided by volumetric thermometry[1] do reduce the risk of unnoticed near-field heating during any single sonication. But because the treatment time in a therapeutical setting is desired to be kept as short as possible, unnecessarily long cooling times are to be avoided that may in turn lead to a cumulative heating effect that is difficult to predict even with volumetric thermometry. The quantification of the heating based on PRF effect is usually limited to the duration of a single sonication due to the baseline drift over long acquisition periods and susceptibility changes such as those induced by transducer displacements. Referenceless thermometry[2] attempts to overcome this limitation, but it cannot be easily used to monitor the near-field heating because of the large monitoring region and strong susceptibility artifacts induced by displacing the transducer. Another option is to precisely model the susceptibility changes associated with each transducer position[3], but this is difficult to perform with mechanical systems having more than two degrees of freedom since it also depends on the susceptibility of the tissue. Instead, we propose an alternative approach to monitor the cumulative near-field heating using volumetric thermometry and including a learning step of reference phase maps for each sonication location as well as a baseline drift correction based on the average apparent temperature change of a non-heated region.

Materials and Methods

A series of HIFU ablations was performed in one leg of an 80 kg pig in accordance with French laws governing the care and the use of animals for research. The animal was ventilated (Respirator paraPac, ResMed SA, France) and maintained under general anesthesia with continuous intravenous injections of ketamine (10 ml/h), propofol (40 ml/h) and curare (0.5 ml/h). The vital parameters were monitored continuously by measuring the cardiac frequency and the rectal temperature. After the treatment the animal was sacrificed and skin and muscle from the near field area were extracted for histological analysis. The animal was installed into a 1.5T Philips Achieva MRI scanner with a Philips clinical HIFU system integrated into the MR table-top. A phased array transducer (256 channels emitting at 1.2MHz) was used to move the focal point electronically along multiple outwards-moving concentric circles with diameters of up to 12 mm. 9 volumetric ablations were sonicated using a mean power of 6.8 ± 1.5 kJ and with intra-treatment cool-down times ranging from 4 to 28 minutes. The transducer could be moved mechanically (3 translations and 2 rotations) for each location in order to sonicate the complete thigh-muscle. The sonication order was selected to maximize the distance between successive ablations. Thermal maps based on the PRF method were calculated from MR images acquired using a spoiled gradient-recalled EPI sequence (TE = 20ms, TR = 37ms, Resolution = 2.5 x 2.5 x 7 mm^3, Flip angle = 20°, EPI-factor = 11, 121-binomial water selection excitation pulse, multi-channel receiver coil, dynamic duration 2.9 s). The near-field temperature was monitored at a plane located 3 cm from the focal point. Five other slices monitored the far-field and target region. After treatment planning, but before the treatment was started, averaged phase reference images were acquired for each planned transducer position These reference images were used to calculate the cumulative thermal maps, which were then compared to the standard thermal maps computed using a phase reference reinitialized at the beginning of each sonication. The baseline drift effect was corrected by measuring the average apparent temperature change over a non-heated region selected around the sonicated area. Since the near-field heating does not have large temperature gradients, a 5 x 5 voxel median filter was applied to reduce the thermal noise level, before the maximal temperature was estimated.

Results and Discussion

Due to the proximity of the transducer to the near-field slice, transducer displacements of 5 cm induced ±30 °C temperature artifacts over the complete slice. These artifacts could not be corrected for with a 2nd order polynomial function. However, by using an appropriate phase references the artifacts were eliminated and the temperature maps showed a pig body temperature of 34.5°C with an accuracy of 1°C in the non heating regions even after 2 hours of monitoring. Some remaining artifacts were located at the borders of the leg, most probably due to stronger baseline drift at those locations. Figure 1 shows the standard and the cumulative thermal maps measured at the end of sonication 3 to 7. Contrary to the standard thermal maps, the cumulative thermal maps provide quantification of the remaining thermal build-up induced by

Figure 1: Standard (A-E) and cumulative (F-J) thermal maps acquired at the end of sonication 3 to 7

previous sonications. Figure 2 indicates the maximum temperature detected with standard and cumulative thermal maps as a function of time for all sonications (1 to 9). After the first and second sonications followed by a cooling period of 4minutes/kJ no thermal build up remains. However after sonication 3, cooling periods of only 1minute/kJ induced accumulative heating at each sonication location. As a consequence, the difference between maximum standard and cumulative thermal maps increased progressively. For the last sonication, the maximum cumulative temperature passed the maximum standard temperature by 5°C. Since cumulative temperature did not exceed 45°C, no necrosis at 3cm from the focal point and no skin burns were identified in histology.

Conclusions

Monitoring of cumulative heating is more complex than standard thermal map monitoring, since it requires quantification of the susceptibility changes induced by movements such as transducer displacement for each sonication location. In addition, artifacts induced by baseline drift should be corrected by using a non-heated region as reference. However, cumulative thermal maps provide a more realistic quantification of the heating produced within the near-field where beam paths of successive sonications overlap. As a consequence cumulative near-field thermal maps, which take into account the complete sonication history, are more reliable than standard thermal maps for detecting skin heating over several sonications.

References

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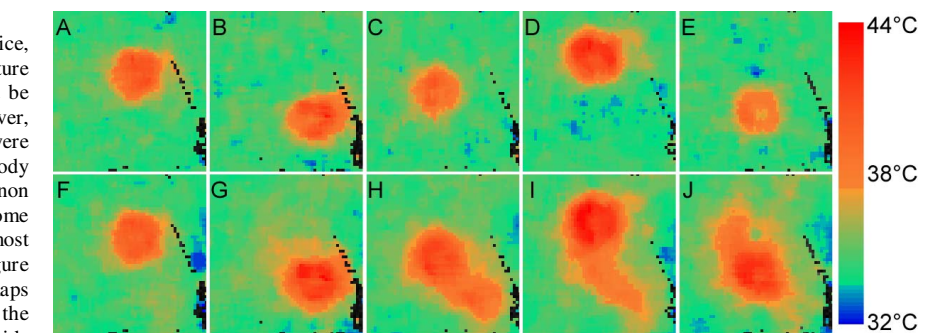[3] Salomir R et al., Leipzig 4th Interventional MRI Symposium 2002 (V-16)
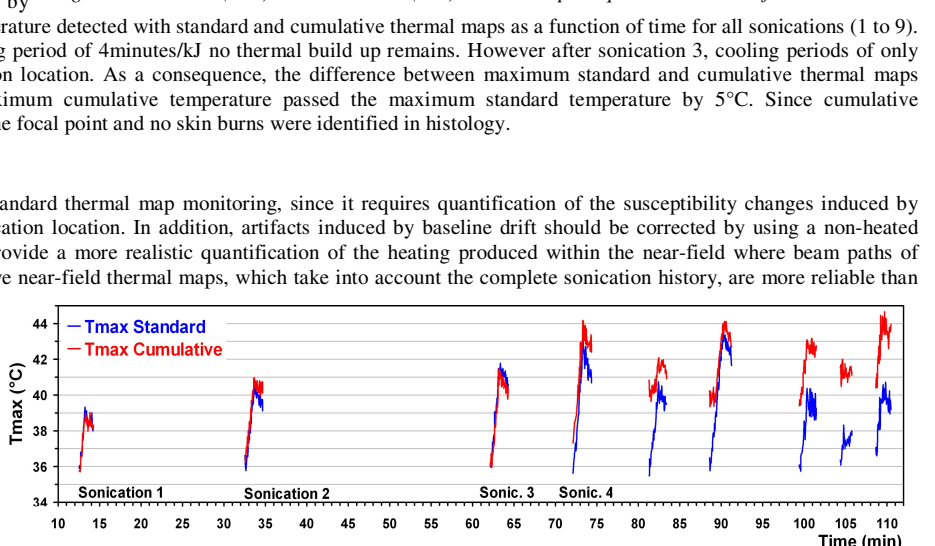
Figure 2: Maximum temperature detected in the near field slice with standard (blue) and cumulative (red) thermal maps for sonication 1 to 9