Contribution of temperature dependent T_1-change, slice thickness and positioning to an artifact in temperature images of FUS heating

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Introduction Proton resonance frequency (PRF) based temperature mapping is commonly used to monitor focused ultrasound (FUS) ablation. Accurate temperature measurements are necessary to calculate the thermal dose, which is an indicator for tissue viability. Because of the small dimensions of the heating region compared to the MR slice thickness, partial volume effects have to be considered [1]. During FUS treatment, the tissue heating is usually monitored in a scan plane transverse through the FUS spot, because partial volume effects along this direction are small. However, it is often desirable to monitor the lesion along its longitudinal direction. In this orientation, an underestimation of the temperature due to partial voluming was expected. However, an additional artifact was seen, shown in Fig. 1. The artifact appears as a dip in the measured temperature in the middle of the heating region where temperatures were expected to be highest. The purpose of this work was to investigate the source of this artifact.

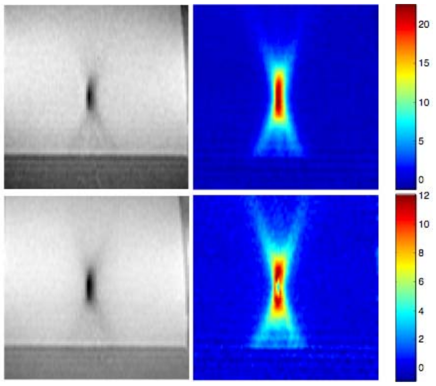

Figure 1: Magnitude and temperature images of two identical FUS heating spots. No artifact is present in the slice centered on the sonication (upper row). In a slice 3 mm off-center, the dip artifact is visible (lower row).

Methods FUS ablation was performed on an InSightec ExAblate 2000 system installed in a 3T GE Signa magnet. After verification of the spot location in the transverse direction, images along the longitudinal direction through the center of the heating spot and with 1-5mm offset to the center were acquired. Imaging was performed using 3 and 5 mm slice thicknesses and different FUS power levels. Additional imaging parameters were TE=12.7ms, TR = 25.5ms, flip angle = 30, FOV=24-32 cm, xres = 256, yres = 128.

We simulated MR temperature measurements of a FUS heating area in MatLab. The heating spot was modeled as a Gaussian temperature distribution in x, y, and z-direction, where the size of the spot was adjustable. A Gaussian distribution of temperature along the longitudinal and transverse axes (a reasonable approximation near the focus [2] and to eliminate FUS beam shape as the source of the artifact) for a beam of full width half maximum size of 2 mm x 8 mm. The temperature distribution was discretized in 0.1 mm elements. From this we calculated the MR signal phase for each element assuming 3T field strength and 12.7 ms echo time as in the experiments. The signal magnitude was set to 1 for no temperature change and reduced by 1-3%/°C temperature rise to simulate the T1 change with temperature, which can be seen as the signal dropout in the magnitude images in Fig. 1. The complex signal was then added along the slice direction to obtain the signal in the 3 and 5 mm slices.

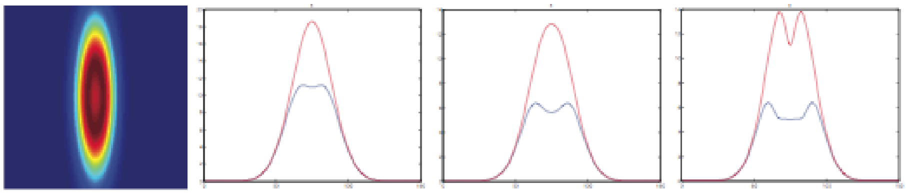

Figure 2: Simulated heating spot showing the dip artifact (5 mm slice). Profiles through the transverse axis of the heating spot are given for a 1 mm offset (left) and 2 mm offset (middle). The blue and red lines show the simulated temperature with and without T1-change. The dip only occurs if the T1-change is considered. When a phase wrap occurs, the dip manifests even without T1-change (right; 2mm offset).

Results The following trends were observed: no dip artifacts occurred for slices centered on the FUS spot and for low FUS power levels. Moving the imaging slice away from the FUS spot creates a dip artifact, which is more pronounced at high FUS power levels. The artifact is larger for thicker slices. The MatLab simulation confirmed the experimental observations (Fig. 2). In addition, it showed that partial volume effect and off-center slice position alone did not create the dip artifact, but that the T1-change with temperature needed to be included in the simulation.

Discussion

Quantitative evaluation of the MR experiments was difficult, because it was not possible to heat the same position in the gel phantom consecutively and have the phantom return to room temperature between sonications within a reasonable amount of time. Depending on the FUS energy used, the spot location needed to be moved after a few sonications which introduced uncertainty of the spot location due to the limited positional accuracy of the FUS system.

In the Matlab simulations, phase wraps due to high temperatures occurring in the central region of the heating spot (see Fig. 2) also created a dip artifact. However, we believe that these phase wraps were not causing the artifact in the MR experiments, since temperature measurements along the transverse direction of FUS spots of the same power settings did not show a temperature high enough to create a phase wrap.

An additional discrepancy was found between simulation and experiment. Whereas in experiment, dips occurred for large heating spots and thin slice thickness, the simulations only resulted in dips for narrow heating spots and thick slices.

Conclusions Experimental results and simulations have demonstrated that off-center slice position together with partial voluming and temperature dependent T1-change can cause a dip artifact in the temperature measurements. Future work includes investigation of the discrepancies between experiment and simulation.

References

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