A Novel Imaging Approach Employing a ±90°-preparation for Fast PRF-based MR Thermometry

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Introduction

Thermal therapies such as laser thermotherapy (LITT) are increasingly performed under MRI guidance as MRI provides unparalleled soft tissue contrast and offers non-invasive temperature mapping using e.g. the proton resonance frequency (PRF) shift method [1, 2]. The PRF shift shows an excellent linearity and is nearly independent of the tissue type. PRF temperature maps are acquired with spoiled gradient echo sequences which use long echo times (TE = 10-20 ms) due to the low PRF-temperature sensitivity of α = 0.01 ppm/K. With increasing TE also TR is prolonged (50-80 ms), and short total acquisition times (TA) are difficult to realize.

In this study, we present a novel imaging strategy for accelerated PRF-based thermometry. The PRF shift is converted into a magnitude change by applying a ±90°-magnetization preparation (similar to flow selective excitation techniques [3]). This preparation, stores the temperature information in the magnitude of the longitudinal magnetization, which can be read out efficiently using rapid imaging techniques.

Materials and Methods

The timing diagram of the MR thermometry sequence with segmented image acquisition is illustrated in Fig. 1. After the collection of N spoiled GRE k-space lines ("k-line") a magnetization preparation interval ("±90°-prep") is inserted. In the preparation, a non-selective +90°-RF pulse rotates the longitudinal magnetization into the transverse plane. After a delay time TI the second non-selective -90°-RF pulse rotates the transverse magnetization back into the longitudinal direction. Next, spoiler gradients are applied to destroy remaining transverse magnetization. Any off-resonance present during TI leads to a phase ϕ of the transverse magnetization. If the first +90° rotation is applied about the x-axis, the temperature dependent phase angle $\phi(\Delta T)$ is given by $\phi(\Delta T) = \alpha \cdot \gamma \cdot TI \cdot B_0 \cdot \Delta T$ [2]. The longitudinal magnetization $M(\Delta T)$ after the -90°-pulse is then $M(\Delta T) = M(T_0) \cdot \cos(\phi)$, where $M(T_0)$ denotes the longitudinal magnetization without temperature changes. Afterwards, $M(\Delta T)$ is read out using a centric reordered GRE acquisition. Temperature changes ΔT can be finally calculated from a reference image $S(T_0)$ prior to heating and images $S(\Delta T)$ during or after heating using the relation $\Delta T = (\alpha \cdot \gamma \cdot TI \cdot B_0)^{-1} \cdot \arccos[S(\Delta T)/S(T_0)]$.

For proof of concept, the ±90°-prepration sequence was implemented on a clinical 1.5 T MR system (Siemens MAGNETOM Symphony, Erlangen, Germany). The sequence was used for temperature monitoring of a LITT procedure (λ = 1046 nm, Δt_{Laser} =80 s; Nd:YAG, mediLas 4060 N, Dornier MedTech, Wessling, Germany) carried out in an agarose-gel (3% agarose, Gd-DTPA/H_2O: 1:800). The following sequence parameters were used: TR/TE = 5.7/2.6 ms, α = 20°, FOV: 220×220 mm^2, SL: 5 mm, matrix: 128^2, bandwidth: 390 Hz/px. The k-space acquisition was segmented into 9 segments each starting with a separate ±90°-preparation. Both 90°-pulses were applied along the x-axis, and a TI of 10 ms was set yielding a total TA of about 800 ms. For verification, the LITT procedure was repeated with the standard PRF method [2] using a spoiled GRE pulse sequence (TR/TE = 20/10 ms, α = 20°, FOV: 220×220 mm^2, th: 5 mm, matrix: 128^2, bandwidth: 120 Hz/px, TA = 2.5 s).

Results and Discussion

In Fig. 2, coronal PRF-based temperature maps of the LITT procedures are overlaid onto a localizer image with the temperature maps obtained via (a) standard GRE phase image subtraction and (b) ±90°-magnetization preparation. Both techniques measure a peak temperature change of about 23 K, as is shown by the temperature profile along the x-direction (Fig 2c). A SNR of 26.2/13.4 was measured for magnitude images of the spoiled GRE/±90°-preparation sequence. From non-heated regions a mean temperature error of ±0.3/±3.5 K (spoiled GRE/±90°-preparation) was estimated. An apparent background temperature rise of about 5-6 K was observed in the ±90°-preparation temperature maps. Nevertheless, both temperature maps are consistent within a range of 10 mm around the laser fiber. The higher temperature error of the ±90°-preperation temperature maps might originate from the reduced SNR, and the background offset could be partly attributed to baseline drifts of the background phase e.g. from gradient-induced eddy currents.

A limitation of this magnitude imaging technique is that all off-resonances lead to a cosine-modulation of the magnitude signal. Thus, small temperature changes result in small phase changes which yield even smaller magnitude changes, so that their detection will be prone to noise contamination. To improve the sensitivity of the ±90°-preparation the direction of the rotation axis of the second 90°-pulse could be changed (cf. Fig. 3). If Θ indicates the angle of the second rotation axis with the x-axis, the reference signal (at T_0) will be proportional to $\cos(\Theta)$ (black solid curve in Fig. 3). During heating, the signal becomes proportional to $\cos(\phi(\Delta T)+\Theta)$ (black dashed curve in Fig. 3). Thus, for a non-vanishing Θ, the sensitivity of the temperature method can be optimized (cf. slope of red dotted curve in Fig. 3 which indicates the ratio of both signals), so that the optimal angle Θ depends on the temperature range of interest. Additionally, Θ will depend and on the SNR. It has to be chosen so that the dephased signal does drop below the noise level, because then the ratio of both signals ($\propto \cos(\phi(\Delta T)+\Theta)/\cos(\Theta)$), and thus, the temperature data would be highly influenced by noise.

With the novel ±90°-preparation approach for PRF-based temperature mapping, image acquisition could be substantially accelerated. TA might be further reduced by combining the ±90°-preparation with a segmented EPI technique. The feasibility of using the proposed ±90°-preparation for PRF thermometry could be successfully demonstrated and might have the potential for highly accelerated PRF temperature mapping.

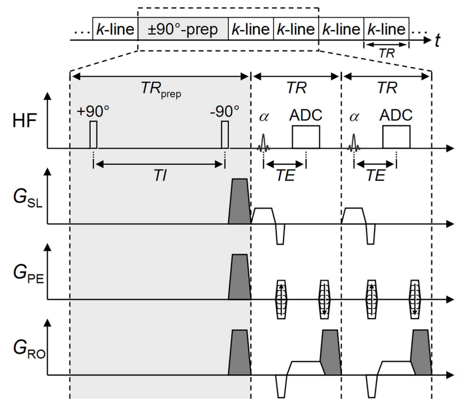

Fig. 1: Pulse sequence diagram of ±90°-preparation technique for PRF thermometry.

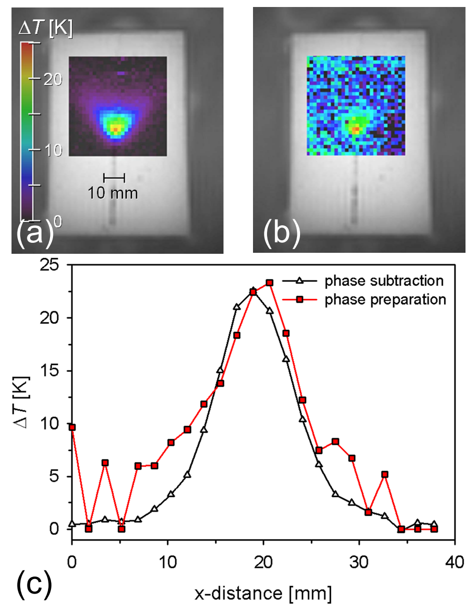

Fig. 2: PRF temperature maps obtained via (a) GRE imaging and phase subtraction and (b) ±90°-perparation. (c) Temperature profile along x-direction through peak temperature.

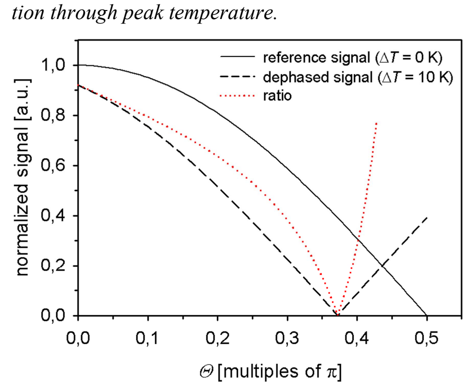

Fig. 3: Theoretical signal after ±90°-prepartion in dependence of the direction Θ of the second rotation axis.

References

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