Proton Resonance Shift based Temperature Mapping with Field Monitoring

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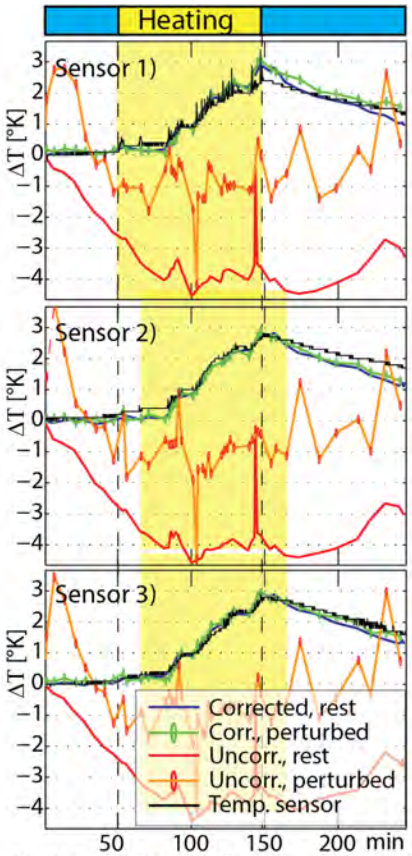
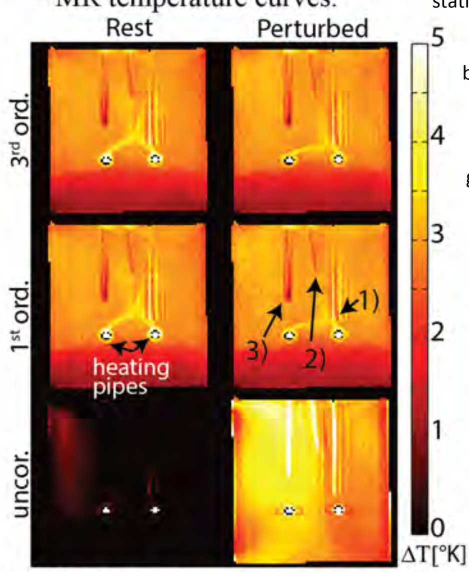


A) Comparison of fluoroptic and MR temperature curves.

Introduction: For measuring local tissue heating, MRI is one of the most frequently used, non-invasive modalities. It is applied for hyperthermia (RF or focused ultrasound induced) treatment monitoring, RF safety assessments, and for validation of thermal models in biology and technology. However, especially the latter applications require to resolve small temperature changes ($\ll 1°K$) over large volumes, which poses significant challenges. Approaches that rely on the temperature dependence of the water proton chemical shift[1] rank among the most sensitive. Although simple to implement in principle, the shift of the resonance is minute ($\approx 10\ ppb/°K$) and easily exceeded by shifts of the main magnetic field as induced by magnet drift, heating of scanner components, cryo-pump fields, or breathing induced field fluctuations ($7-40\ ppb$ in the brain). To correct for field fluctuations, relatively temperature-stable lines of C-H bonds can be used, either provided externally by small oil containers[2] or internally by subcutaneous or interstitial fat. In this case the field drift can be corrected based on the full image only, while inter-shot variations are neglected. Techniques based on voxel internal references typically offer lower sensitivity and require abundance of water and fat in each voxel of the entire region of interest[3]. In order to address these concerns we apply magnetic field monitoring in this work to measure and to correct for field variations in every interleave of the acquisition with up to 3rd order in space, using an array of 16 NMR magnetic field probes mounted around the ROI.

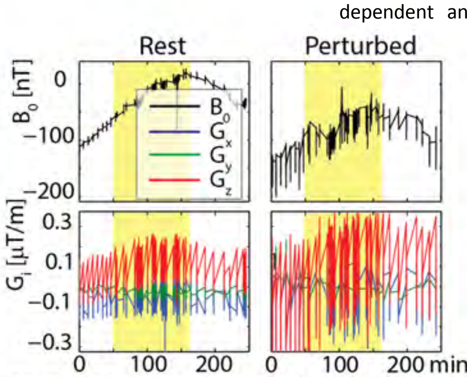
Methods: The hexafluorobenzene NMR field probes were temperature compensated up to less than $1\ ppb/°K$ by cancelling the effects of all involved bulk-susceptibility- and chemical shifts. An array of 16 NMR field probes[4] was mounted on an 8-channel head coil of a clinical 3T scanner (Achieva, Philips Healthcare, Best, Netherlands). The field evolution of a Cartesian 2D gradient echo sequence (TE $20\ ms$; TR $200\ ms$; $(1.7 \times 1.7 \times 2.5) mm^3$) was monitored up to 3rd order in space over $250\ min$. Image reconstruction was performed on the monitored trajectory up to 1st and 3rd order respectively; for comparison the image series was also reconstructed based on the field evolution of the first dynamic ('uncorrected'). The temperature rise was calculated by taking the phase difference of every image relative to the first, based on a temperature shift of $8.7\ ppb/°K$ of the phantom filling ($10\ g/l$ copper sulphate pentahydrate aqueous solution). Two tubes passing the phantom in z direction were filled with warm phantom solution for heating. For validation, three fluoroptic temperature probes (Neoptix, Canada) were positioned in the acquired transverse slice (as marked in B 1)-3)) measuring concurrently with the scanner. The phantom stood $12\ h$ in the scanner room to ensure thermal equilibrium at the beginning of the series. Subject breathing was simulated in every other acquisition by moving a $10\ cm$ water sphere in the bore causing perturbations on the order of several $10\ nT\ /\ \ 0.1\ \mu T/m$ as seen in plot C).

Results: A)1)-3) shows the temperature curves based on the fields monitored up to 3rd order in the scanner at rest (green solid line) and perturbed (green dashed line) in comparison to the three temperature sensors 1)-3) in good agreement with only $0.5°K$ maximum deviation over $250\ min$. In comparison the scanner field drift and the induced perturbations caused large temperature errors when no correction was applied (red lines). **B)** shows the maximum temperature rise in each voxel over the entire duration. As seen, the induced field perturbations had a very minor impact with less than $0.14\ °K$ deviation on average over the whole slice and over the whole time series of more than four hours. Even restricting to only compensating field drifts of 1st order in space worsened the results only slightly by roughly doubling the error. However the influence of the first order is significant as exemplified by the measured static baseline field evolutions in 1st order as shown in **(C).** Although the field drifts seem to temporally correlate with the measured temperature curve, it has to be noted that the ramp in B_0 is already present before heating and might be related to the scanning itself but already prevented an uncorrected acquisition of the initial temperature baseline.



B) Maximum temperature rise; 1)-3) positions of temperature sensors.

Conclusion: Scanner field drifts and subject-induced perturbations prevent robust temperature mapping based on the proton resonance shift if not accounted for. Corrections based on field monitoring are a generic means for effective compensation of perturbations with high temporal dynamics. This allows correcting for changes in the gradient waveforms too (e.g., due to changes in the oscillatory behaviour) which are known to be temperature dependent and can cause phase errors due to echo shifts. This is particularly important in high gradient duty cycle acquisitions using fast read-outs and gives headroom in the sequence for suppression of other detrimental effects such as flow and motion. Even in phantom experiments corrections up to first order in space were found to be essential. The proposed method requires no internal nor external reference and no additional acquisition time. The field dynamics can be measured for each interleave, which is not possible using fiducials such as oil flasks that first need to be resolved or selectively excited for an effective correction. The provided results suggest that temperatures can be measured by MR with accuracies of fractions of $1°K$ even in the presence of strong (>33 *ppb*) field perturbations. Field monitoring is further expected to enhance alternative temperature mapping methods e.g. based on relaxometry or quantitative diffusion. The field estimate in the sample is based on the assumption that the generators of the field perturbation reside outside the volume of the field probe array, which can be violated in certain in-vivo scenarios, but are known to be fulfilled for breathing induced field fluctuations in the head.



C) Static baseline field fluctuations in for each interleave up to 1st order for no perturbation (rest) and with.

Refs: 1) Ishihara, MRM (1995) 2) Poorter JMRB (1994), 3) Warren, Science 322 (2008), 4) DeZanche MRM (2008)