Heating of fat leads to significant temperature errors in PRFS based MR thermometry

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Introduction Reliable thermometry is a prerequisite during thermal therapy for monitoring and controlling temperature and thermal dose. MRI offers both excellent soft tissue contrast for target visualization and the possibility for noninvasive thermometry, and can therefore be used as a noninvasive guiding tool for thermal therapy. The currently most widely used MR thermometry (MRT) technique is proton resonance frequency shift (PRFS) based MRT. It exploits the temperature dependence of the proton resonance frequency (PRF) of water. The PRF at a certain location inside an object is proportional to the magnetic field experienced by the hydrogen nuclei at that location. The temperature dependence of this magnetic field at the nucleus B_{nuc} can be modeled as a shielding of the local macroscopic magnetic field in the object $B_{mac}(T)$ by the temperature dependent parameters $\sigma(T)$ and $\chi_o(T)$, which are the proton electron screening constant and the susceptibility of the object at the considered location, respectively [1]:

$$B_{nuc}(T) = (1 - \sigma(T) - \frac{2}{3}\chi_o(T))B_{mac}(T) \qquad (1)$$

The macroscopic magnetic field B_{mac} is a function of the susceptibility distribution within the object $\chi_o(T)$, the main magnetic field B_0, the susceptibility of the object's environment χ_e and the geometry of the object.

In current practice, the temperature dependent parameter which is exploited for PRFS based MRT is the proton electron screening constant of water σ_{water} ($d\sigma_{water}/dT$ = 0.0098 ppm/°C [2]). The temperature dependence of the proton electron screening constant of fat σ_{fat} is very small compared to that of σ_{water} ($d\sigma_{fat}/dT$ = 0.00018 ppm/°C [2]). Without fat suppression, this effect would be a source of significant errors in PRFS based MRT, because temperature related changes in B_{nuc} are extracted from the phase difference $\Delta\varphi$ between successive gradient echo MR images. In voxels containing both water and fat, the $\Delta\varphi$ of the sum signal is not representative for the temperature change. Therefore, fat suppression techniques are always employed in PRFS based MRT.

Another source of errors is the temperature dependence of the susceptibility of the object. Temperature induced changes in χ_o alter B_{mac}. The resulting errors are therefore non-local, since such changes affect the PRF, and hence measured temperature, of all water protons that experience the B_{mac} change. The influence of $d\chi_{o,water}/dT$ on the outcome of PRFS based MRT is expected to be small, since $d\chi_{o,water}/dT$ = 0.00199 ppm/°C [2]. The temperature dependence of the susceptibility of fat, $\chi_{o,fat}$, however, is reported to be much higher: $d\chi_{o,fat}/dT$ = 0.0094 ppm/°C [1]. The application of fat suppression techniques does not correct for this non-local effect, which has often been ignored in literature on PRFS based MRT. In this work we focused on quantification of the impact of $d\chi_{o,fat}/dT$ on PRFS based MRT in the breast during thermal therapy. Simulations were performed in an anatomical breast model to calculate the changes in the B_{mac} field in glandular tissue caused by temperature induced changes in the surrounding fat. The impact of the found changes in B_{mac} on PRFS based MR temperature maps was assessed.

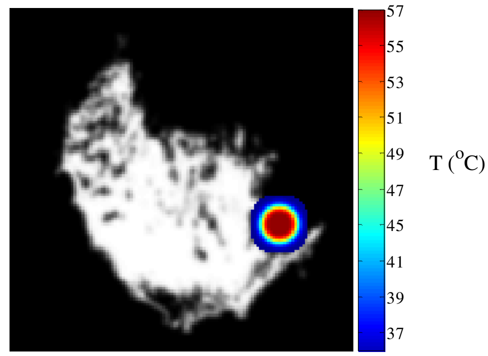

Figure 1 Segmented glandular tissue (white) surrounded by fat (black) of a single slice through the 3D breast model. In color, the location and temperature distribution of the thermal spot is shown.

Materials & Methods ***Model*** Based on a high resolution 3D breast scan of a female volunteer, glandular tissue of a single breast was segmented. Outside of the segmented glandular tissue, it was assumed that only fat was present. To simulate the effect of a thermal intervention, a spherically shaped thermal spot (TS) with a radius of 10 mm was placed in this breast model. In the TS, a stationary Gaussian temperature distribution was assumed with a maximum temperature of 57 °C. The following susceptibility values were used for glandular tissue $\chi_{o,glandular} = -9.05\cdot10^{-6}$ and for fat $\chi_{o,fat}(T) = -7.79\cdot10^{-6} + 0.0094\cdot10^{-6}\cdot\Delta T$ [3,1] with ΔT being the temperature rise from body temperature (T_{body} = 37 °C). For both the breast model without the TS and with the TS, the susceptibility was calculated per voxel, based on the glandular/fat-fraction, and the local temperature. Subsequently, the B_{mac} field was calculated using these susceptibility distributions. ***Calculation*** Input for all simulations is the susceptibility distribution $\chi_o(\vec{r})$, which is expressed as a permeability distribution using: $\mu_r(\vec{r}) = 1 + \chi_o(\vec{r})$. Since $\nabla\times B_{mac} = 0$ inside the bore of the scanner, and using the general equation $\nabla\times(pQ) = -(Q\times\nabla p)+(p\nabla\times Q)$ for any scalar field p and any vector field Q, in combination with $B_{mac} = \mu_0\mu_r H_{mac}$ and $H_{mac} = H_0 + H_{eq}$, we derive the recursive equation $\nabla\times H_{eq} = H_{eq}\times\mu_r^{-1}\nabla\mu_r$. The solution of this equation may be written as a perturbation series; of which we need only the first term ($(\mu_r - 1)$) since (μ_r-1) is small: $\nabla\times H_{eq} = \mu_0^{-1}B_0\times\nabla\log\mu_r$ which represents a 'free' current density distribution: $J_{eq} = \mu_0^{-1}B_0\times\nabla\log\mu_r$. This J_{eq} serves as an equivalent current density distribution to model the effects of boundaries between regions of constant μ_r. The calculation of the B_{mac} field resulting from this equivalent J_{eq} has been carried out in the Fourier domain, in which the calculation of the convolution of the Green's function with the spatial J_{eq} distribution is carried out as a simple multiplication. ***Determination of temperature error*** Changes in the magnetic field distribution, ΔB_{mac}, due to susceptibility changes in heated fat were quantified by subtraction of the pre- and post heating B_{mac} outcome. For all voxels containing glandular tissue, this field change was expressed in ppm. The resulting temperature error was determined using $\Delta T_{err} = \Delta B_{mac}$ [ppm]/0.0098.

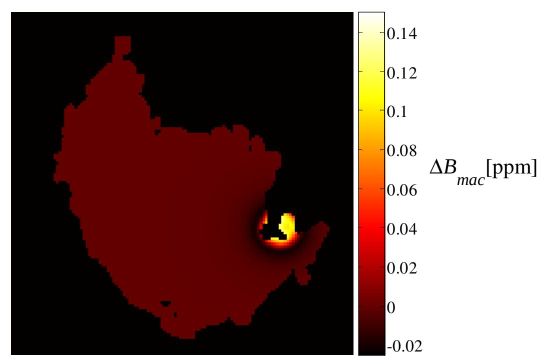

Figure 2 ΔB_{mac} changes in ppm in the glandular tissue due to susceptibility changes in the surrounding heated fat. The maximum ΔB_{mac} in the glandular tissue is 0.13 ppm, corresponding to an error in the temperature measurements of ΔT_{err} = 13.3 °C.

Results Figure 1 shows a single slice through the 3D breast model. In white, the segmented glandular tissue is depicted, surrounded by fat in black. On top of this, the location and temperature distribution of the TS are shown. Figure 2 shows ΔB_{mac} within the same slice. For illustrative purposes, only voxels containing glandular tissue, i.e. those voxels giving signal in a fat-suppressed PRFS-based MRT scan, are depicted. Clearly visible are the field disturbances in these voxels due to the susceptibility changes in the surrounding fat. The maximum ΔB_{mac} within the glandular tissue of the 3D breast model was 0.13 ppm, corresponding to ΔT_{err} = 13.3 °C.

Discussion and conclusion Our results show that the temperature dependence of the susceptibility of fat leads to significant errors in temperature measurements in glandular tissue during thermal interventions in fatty tissues like the female breast. Important to stress is the fact that fat suppression is not a solution for this effect. In future work we will simulate other anatomies and heating patterns and aim for experimental validation of our simulations in actual MRT experiments.

References [1] de Poorter J. Magn Reson Med. 1995 Sep;34(3):359-67 [2] Stollberger R. J Magn Reson Imaging. 1998 Jan-Feb;8(1):188-96 [3] Hopkins J. Magn Reson Med. 1997 Apr;37(4):494-500