Influence of magnetic susceptibility on absolute temperature as measured directly from the water/fat frequency shift.

Paul Baron[1], Martijn de Greef[1], Roel Deckers[1], Chris J.G. Bakker[1], Job G. Bouwman[1], and Lambertus W. Bartels[1]
[1]University Medical Center Utrecht, Utrecht, Utrecht, Netherlands

PURPOSE:
Temperature mapping during MR-guided thermal therapies is important to ensure that tissue necrosis has occurred at the target zone and for preventing damage to healthy tissue. The commonly employed techniques (based upon the Proton Resonance Frequency Shift and/or T_1) measure changes in temperature and frequently assume a baseline temperature of 37°C. However, calculation of the thermal dose, an important indicator of tissue damage, requires knowledge of the absolute temperature over time. Deriving the temperature directly from the water/fat frequency shift (WFS) has previously been proposed [1] as a method for obtaining absolute temperature measurements. An assumption of this method is that the intra-voxel water and fat components experience the same magnetic field, which may not be true for all water/fat (w/f) distributions. The purpose of this study was to investigate the influence of the spatial magnetic susceptibility distribution on absolute MR thermometry, both in case of a heterogeneous w/f distribution (pork meat) and of a homogenous w/f distribution (margarine).

METHODS:
Theory: For a given tissue susceptibility distribution (χ), electron shielding constant (σ), and object orientation with respect to the main magnetic field (B_0), the induced nuclear magnetic field (B_{nuc}) may be calculated using a Fourier-based algorithm [2]. Eq. 1 shows that the influence of magnetic susceptibility is completely removed, when the induced magnetic fields of an object in three orthogonal orientations (x,y,z) with respect to B_0 are averaged, leaving only the electron shielding constant:

$$B_{av,nuc} = \frac{1}{3}\left[-\sigma + FT^{-1}\left[\left(\frac{1}{3}-\frac{k_x^2}{k^2}\right)FT(\chi)\right] - \sigma + FT^{-1}\left[\left(\frac{1}{3}-\frac{k_y^2}{k^2}\right)FT(\chi)\right] - \sigma + FT^{-1}\left[\left(\frac{1}{3}-\frac{k_z^2}{k^2}\right)FT(\chi)\right]\right]B_0 = -\sigma B_0 \qquad \textbf{(Eq. 1)}$$

where $k^2=k_x^2+k_y^2+k_z^2$. In this paper we used this property to design an experiment to show the effects of susceptibility and chemical shift separately.
Experiment: A spherical holder (r= 4 cm) was in one experiment filled completely with margarine (40% fat) and in a subsequent experiment completely filled with pork meat and placed inside the bore of a 3-T MRI scanner (Achieva, Philips Healthcare, Best, The Netherlands.) The samples were kept at room temperature (21.3°C). A reference cartesian 3D coordinate system (x_{obj}, y_{obj}, z_{obj}) was defined fixed to the sphere with its origin in the center of the sphere. For each of the three object coordinate axes positioned parallel to the main magnetic field, a 2D spectroscopic scan was acquired (PRESS, FOV = 250×250 mm^2, slice thickness = 10 mm, $N_x \times N_y$ = 50×50, TR = 400 ms, TE = 30 ms, BW = 1kHz, number of samples =256) with the slice intersecting the center of the sphere such that the same region was imaged for each orientation. One volumetric shimming procedure was performed containing the whole sphere, prior to the experiment. For each voxel the WFS was determined by fitting a two peak model to the spectral time signal using in-house developed software. The measured absolute temperature (°C) was defined as [3]:

$$T_{abs} = 21.0 + (WFS - 3.50)/-0.010 \qquad \textbf{(Eq. 2)}$$

The average of the three orientations (each with NSA=1) was compared to the measurement with x_{obj} parallel to B_0 ($x_{obj} /\!/ B_0$) and with NSA=3.
Simulations: To study the influence of w/f magnetic susceptibility distribution on the measured absolute temperature for an in vivo situation, simulations of spectroscopic imaging were performed. A high resolution (0.63×0.63×0.63 mm^3) fat suppressed T_1-w 3D scan of the breast was segmented [4] to create a realistic susceptibility distribution. Then, fat, fibro-glandular tissues, and air were assigned magnetic susceptibility values of -7.44 ppm, -8.98 ppm and 0.36 ppm [3], respectively. Then the induced magnetic field was calculated. The theoretical MR signal of one spectral peak (either water or fat) was attributed to the water and fat voxels (T_{abs} = 37°C, $\omega_w = \gamma B_{nuc}$, ω_f = WFS+ γB_{nuc}, $R2^*_w = R_2{}^*_f$ = 40 s^{-1}, $A_w = A_f$=1) and spectroscopic imaging (TE= 1,2,…,24 ms, transverse slice) was simulated with down sampled resolution (in-plane = 5×5 mm^2 , ST=10 mm). The WFS obtained with a two peak fitting model was used to calculate measured absolute temperature maps with Eq. 2.

RESULTS:
Experiment: For margarine (Fig. 1: upper panel), the absolute temperature measured for $x_{obj} /\!/ B_0$ was 26.0±1.2 °C. The mean temperature of the average of the three orientations was 26.0±1.1°C. For pork (Fig. 1: lower panel), the absolute temperature measured for $x_{obj} /\!/ B_0$ was 19.9±11.9 °C. The mean temperature of the average of the three orientations was 18.4±5.1°C.
Simulations: Fig.2 shows the simulation of the measured absolute temperature in the breast. For the indicated ROI, the mean temperature measured was 42.2±15.9°C (N=161).

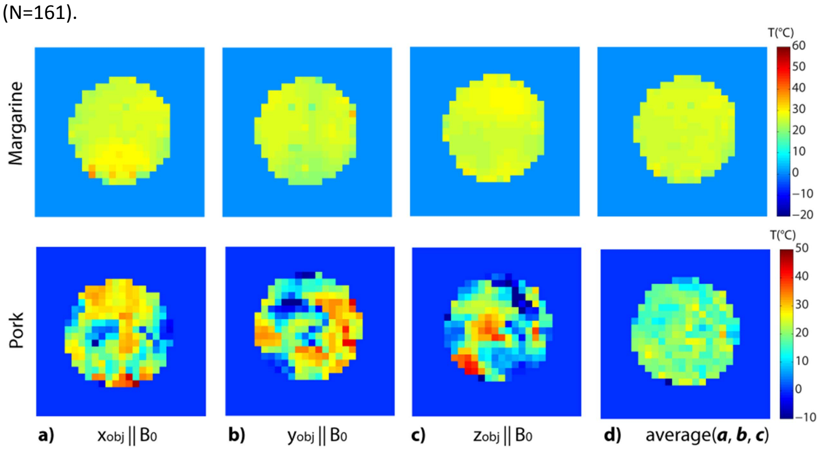

Fig. 1. (a-c) The absolute temperature measured for a sphere of margarine and pork for the three object orientations and **(d)** the average of the three orientations.

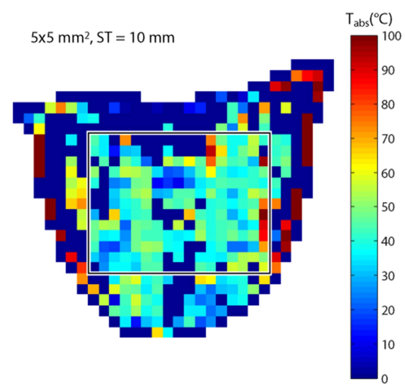

Fig. 2. The simulated absolute temperature in breast tissue.

DISCUSSION & CONCLUSION:
The results show that for a heterogeneous w/f distribution, such as in the breast, the susceptibility distribution influences the observed absolute temperature (order of variation: SD ≈ 15°C). This was shown for a rotation experiment and with a simulation. The results may partly explain the large temperature measurement variations (SD = 14°C) previously reported in the breast using line scan echo planar spectroscopic imaging [5]. The temperature measurements in margarine were more homogeneous. The difference in (susceptibility independent) temperatures measured in margarine and pork (Fig 1, column d) may be explained by other factors such as pH [5]. Additionally, the difference between the probe reading and temperatures measured suggests that the offset and slope of Eq. 2 may need to be calibrated per tissue type. The performance of absolute thermometry in more homogenous w/f tissues (fatty liver, bone marrow) is under our investigation.

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