The influence of background gradients in multi gradient-echo MR thermometry

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Introduction Absolute MR thermometry (MRT) can be performed by exploiting the difference Δf between a temperature sensitive proton resonance frequency (PRF) (e.g. of water) and a temperature insensitive reference PRF (e.g. of fat). A time efficient technique for acquiring spatially resolved PRF information is the image-based method using a multi gradient-echo (mGE) sequence [1]. In mGE based MRT, multiple (n) gradient-echo images are acquired at echo times $TE_i = TE_1 + (i\text{-}1)\cdot\Delta TE$ for $i = 1,2,\ldots, n$, with TE_1 the echo time of the first gradient-echo image and ΔTE the echo spacing. This yields a discretely sampled time signal containing spectral information of the substances involved, which can be post-processed into temperature data [2-5].

The outcome of mGE based MRT may be affected by the presence of background field gradients G'. Background gradients lead to echo shifts in gradient-echo acquisitions when G' is aligned with the readout gradient. The shifted echo time TE_{shift} depends on the chosen echo time TE, the strength of the readout gradient lobe G_R and on the strength and sign of G', as given by equation 1. In mGE based MRT post-processing it is assumed that the signal is acquired at echo times TE_i. However, in case of echo shifting, the echo occurs earlier or later than the chosen TE_i, which alters the spectral properties of the mGE signal. Without correction, such shifts lead to errors in the outcome of the fitting procedure, regardless of the post-processing technique used. In this work we aimed to investigate the impact of background gradients in mGE based MRT. Furthermore, an echo shift correction method is proposed and its feasibility is demonstrated.

$$TE_{shift} = \frac{TE}{\frac{G'}{G_R} + 1} \qquad (1)$$

Materials & Methods In vitro scans were performed on a 3-T whole body system (Achieva, Philips, Best, The Netherlands). Ethylene glycol (EG) was used as a test fluid for all scans, since the temperature dependence of the frequency difference Δf_{hm} between the hydroxyl (h) and methylene (m) group in EG is well known [6]:

$$T_{EG}[^{o}C] = 193.35 - 102\cdot 10^{6}\cdot \Delta f_{hm}[Hz]/\gamma B_0 \qquad (2)$$

with B_0 the main magnetic field strength. In this work G' was deliberately maximized by the shape of the phantom which was a flat cylinder (length 4 cm, radius 4.5 cm), placed with its longitudinal axis perpendicular to the main magnetic field. The cylinder was filled with EG at constant temperature and with a homogeneous temperature distribution. The EG temperature T_{EG} was measured using fiber-optic temperature probes (Luxtron, Santa Clara, CA) during all scans. ***Acquisition*** Four coronal mGE scans were made, each using a different readout direction (*dir*): **1.** *dir* = Feet-Head (FH) **2.** *dir* = HF **3.** *dir* = Right-Left (RL) **4.** *dir* = LR. For all scans: G_R = 27,1 mT/m. In our setup, with B_0 = 3T and T_{EG} = 21.2 °C, $\Delta f_{hm} \approx$ 215 Hz. TE_1 = 1.8 msec, ΔTE = 1.8 msec, which corresponds to a spectral bandwidth $SBW \approx$ 555 Hz. A total of 32 echoes was acquired and asymmetric read-out was performed using rewinder gradients. TR = 60 msec; $\alpha = 30^{\circ}$; FOV 128x128 mm^2; acq.matrix 84x84; acq.voxel size 1.52x1.52x10 mm^3; rec. matrix 96x96. ***Post-processing*** The modulus signal S of a voxel containing the two spectral components h and m at echo times TE_i is given by:

$$S(TE_i) = \sqrt{A_h^2 e^{-2R^*_{2,h}TE_i} + A_m^2 e^{-2R^*_{2,m}TE_i} + 2A_hA_m e^{-(R^*_{2,h}+R^*_{2,m})TE_i}\cos(2\pi\Delta f_{hm}TE_i + \Delta\varphi_{hm})} \qquad (3)$$

with A_h and A_m the effective spin densities (including effects of the longitudinal relaxation rate T_1), $R^*_{2,h}$ and $R^*_{2,m}$ the effective transverse relaxation rates, and $\Delta\varphi_{hm}$ the phase offset difference between the two components in radians. For all four scans, Δf_{hm} was found by fitting the modulus signal in the time domain to the signal model as given in equation (3) per voxel [7]. To investigate the echo shift correction method, the fitting procedure was applied twice. In the first approach, the chosen echo times TE_i were used in the fitting process. In the second approach, a correction step was implemented. This step involved the calculation of the shifted echo times $TE_{shift,i}$. These $TE_{shift,i}$ were calculated per pixel using equation (1). The required G' was determined per pixel from field gradient maps which were computed for each scan from the phase images, in the direction of G_R. Finally, for both fitting approaches, absolute temperature maps were computed from the resulting Δf_{hm} data using equation (2).

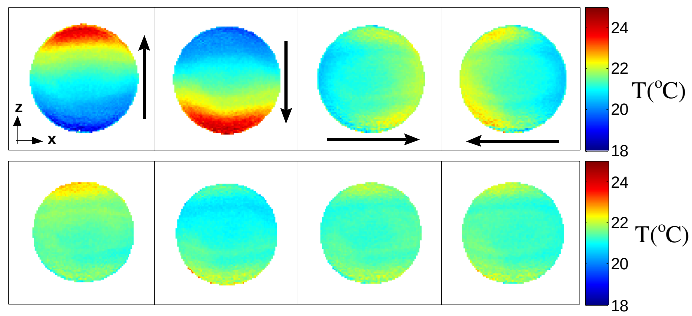

Figure 1 Absolute temperature maps of EG fluid at constant, homogeneous temperature (T_{EG} = 21.18 ± 0.15 °C, optical fiber). Top row: uncorrected maps all show an apparent temperature gradient in the direction of G_R (which is indicated by the arrow). Bottom row: corrected temperature maps.

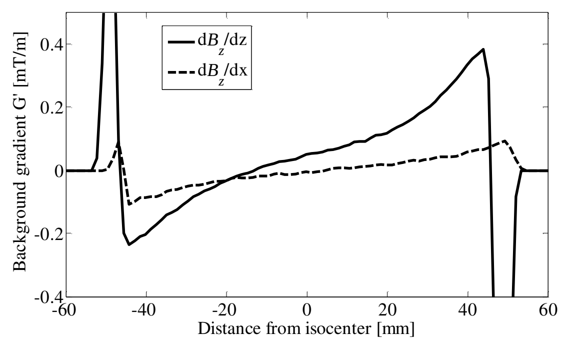

Figure 2 Two G' profiles, one in FH (dB/dz, solid line) and one in LR (dB/dx, dotted line) direction. G' is nonlinear and has maximum strength in the FH direction.

Results The top row of fig.1 shows four absolute temperature maps of EG at four different readout directions. The direction of G_R is indicated by the arrow. An apparent temperature gradient in the direction G_R is clearly visible. The temperature range and average temperature T_{av} per scan is: **1.** 17.9-24.5 °C (T_{av} = 21.3 °C) **2.** 19.2-24.8 °C (T_{av} = 21.5 °C) **3.** 20.1-22.6 °C (T_{av} = 21.4 °C) **4.** 19.9-23.2 °C (T_{av} = 21.4 °C). The optical temperature measurements gave T_{EG} = 21.18 ± 0.15 °C during all scans. The bottom row shows the temperature maps after correction. The apparent temperature gradient is reduced. However, residual temperature errors are visible. After correction, the temperature range and T_{av} per scan is: **1.** 20.7-23.0 °C (T_{av} = 21.5 °C) **2.** 20.4-23.3 °C (T_{av} = 21.2 °C) **3.** 20.4-22.3 °C (T_{av} = 21.4 °C) **4.** 20.7-22.7 °C (T_{av} = 21.4 °C). Figure 2 shows two G' profiles through the center of the phantom, in the FH and LR direction. The maximum G' value in the phantom is 0.4 mT/m which corresponds to a maximum echo shift of 1.4% of TE_i.

Discussion & Conclusion Our experiments show the impact of background gradients on the mGE based MRT technique. Such gradients shift the acquired echoes, and therefore alter the spectral properties of the mGE signal. This echo shift effect not only influences mGE based temperature mapping. It affects the spectral properties of all MR signals acquired using a multi gradient-echo sequence. It therefore has implications in the field of T_2^* relaxometry as well. Our correction method largely adjusts for this effect. However, the residual temperature errors in the corrected temperature maps indicate that other processes, e.g. through-plane gradients, may be involved as well. Currently we are working the assessment on the implications of this echo shift effect in *in vivo* situations as well as on improvement of the correction methods by understanding and quantification of all underlying factors.

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