# Accurate temperature measurements in the presence of field inhomogeneities

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**Target audience:** Clinical researchers involved in MR-guided thermal ablation work or, more generally, in field mapping.

**Purpose:** The goal of this work is to improve the measurement of temperature in the presence of $B_0$ inhomogeneities. Transcranial MRgFUS can be used to treat essential tremor[1,2] near the thalamus. However, $B_0$ inhomogeneities near the treatment target often prevent accurate measurement[3] of the therapy heating at the target site. With proton resonance frequency (PRF) thermometry, phase changes are converted into temperature changes by mapping the echo time, *TE*, to temperature. In the presence of field inhomogeneities, MR echoes may be translated and/or spread in k-space, potentially making the 'true' echo time vary spatially within the imaged object and take on values that differ from the nominal user-input *TE* value. Errors in *TE* lead to errors in temperature, and the purpose of this work is to describe and correct for these errors.

**Methods:** Consider a dual-echo gradient-echo sequence with imaging bandwidth $BW_1$ and $BW_2$ and nominal user-input echo time $TE_1$ and $TE_2$ for the two echoes, respectively. A relative temperature measurement could be obtained independently from each echo, and combined through a weighted sum with weights $w_1$ and $w_2$: $\Delta T = (w_1\Delta T_1 + w_2\Delta T_2)/(w_1 + w_2)$. It can be derived, when selecting weights such that $w_2 = -w_1 \times BW_2/BW_1$, errors in $\Delta T_1$ precisely cancel out errors in $\Delta T_2$, giving rise to a temperature measurement immune to field inhomogeneities. Ideally, however, weights should be chosen to optimize the temperature-to-noise-ratio (TNR), based on expected signal strength and/or *TE* value, and constraining the choice of these weights would have a TNR penalty. Alternately, inhomogeneity-induced errors in *TE* could be explicitly calculated, allowing any weights $w_1$ and $w_2$ to be subsequently selected for optimum TNR. With $\Delta\phi$ the measured temperature-induced phase shift, and $\tau$ the evolution time available for phase accumulation (in most sequences $\tau$ is simply equal to *TE* but in more exotic cases it may take on different and even negative values[4]), one can obtain:

$$\Delta\tau_1 = -\frac{\tau_1 \times (\Delta\phi_1 \times \tau_2 - \Delta\phi_2 \times \tau_1)}{\Delta\phi_1 \times \tau_2 \times (BW_1/BW_2) - \Delta\phi_2 \times \tau_1}, \quad \frac{\Delta\tau_1}{\Delta\tau_2} = \frac{BW_2}{BW_1} \times \frac{\tau_1}{\tau_2}.$$

However, these equations require $BW_1 \neq BW_2$. Different bandwidths lead to different spatial distortions in the presence of field inhomogeneities, making it difficult to perform pixel-by-pixel processing. A more general but more computationally-involved method is introduced below that remains valid even for a single-echo sequence or for a dual-echo sequence with $BW_1 = BW_2$.

Given a field map $B_0(\vec{r})$, spatial gradients in $B_0(\vec{r})$ are responsible for shifting signal in k-space. A pulse-sequence specific function $f_s$ is introduced that returns the time at which any given k-space point is sampled. The error in the echo time is given by:

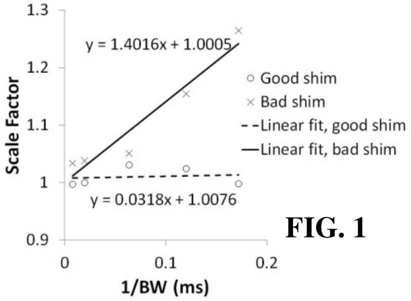

**FIG. 1**

$$\Delta TE_{j,i}(\vec{r}) = f_s(\Delta\vec{k}_{j,i}) - TE, \text{ with } \Delta\vec{k}_{j,i}(\vec{r}) = 2\pi \times \gamma \times \hat{\tau}_{j,i} \times \nabla B_{0,i}(\vec{r}), \text{ and } \hat{\tau}_{j,i} = TE_j + \Delta TE_{j,i-1},$$

where $j$ is the echo number, $i$ the iteration number, $\Delta TE_{j,0} = 0$. Corrected temperature measurements are obtained from corrected $\tau$ values. The field map also needs to be corrected in the process, hence the '$i$' dependence in $B_{0,i}$. For example, with a dual-echo sequence, the field map would be obtained by comparing the phase of the two echoes and dividing by $(TE_{2,i} - TE_{1,i})$, and thus is corrected from one iteration to the next. A very small number of iteration (about 3) appeared to be sufficient in the present work.

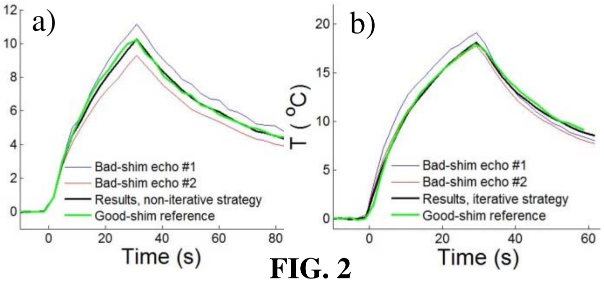

**FIG. 2**

**Results:** A series of thermometry experiments were performed by heating a gel phantom using an ultrasound transducer inside a 3 T MR system (55 W for 20 s, 1.5×1.5×5 mm$^3$, 128×128, *TE/TR*=10/17 ms, 30$^o$ flip angle). Temperature measurements were made in the presence of field inhomogeneities (introduced by intentionally de-adjusting shim parameters) as well as with carefully-shimmed scans and using a number of different settings for the sampling bandwidth, *BW*. Figure 1 shows that as expected the presence of field inhomogeneities cause errors in the measured temperature values. These errors take the form of a multiplicative factor that increases linearly with 1/*BW*, with a slope that depends on local field gradients at the transducer's focus. Through careful shimming, local field gradients could be removed, leading to accurate measurements at all sampled 1/*BW* settings ('o' symbols in Fig. 1). The proposed work aims at enabling accurate measurements despite field inhomogeneities.

Results in Fig. 2a were reconstructed with weights $w_1$ and $w_2$ chosen as described above ($BW_1 = -BW_2$, $w_1 = w_2$, 37 W for 30 s, $TE_1/TE_2/TR$ = 7.2/17.8/25 ms), and reference results were obtained from carefully-shimmed scans. For Fig. 2b, a sequence with $BW_1 = BW_2$ was used instead, and data were reconstructed with the iterative method described above (57 W for 30 s, $TE_1/TE_2/TR$ = 6.2/16.7/24 ms). In both cases please note that corrected results obtained in bad shim conditions, once reconstructed as proposed, were in good agreement with reference good-shim results.

**Discussion:** PRF thermometry measures temperature-induced field changes, and is in nature a field-mapping method. The type of errors described and corrected for here would presumably be present in any field-mapping MR application, not just thermometry. These errors can be quite significant, especially when a narrow imaging bandwidth is chosen to help boost SNR, and errors by as much as 26% were readily observed and corrected for.

**Conclusion:** Field inhomogeneities create errors in temperature measurements, which can be detected and corrected using the proposed strategies.

**References:** 1. Elias et al, N Engl J Med 369:7 (2013). 2. Lipsman et al, Lancet neurology. 12:5 (2013). 3. Sprinkhuizen, Chapter 7, Ph.D. thesis (2010). 4. Madore et al, MRM 66:658(2011). Support from grants R01CA149342, P41EB015898 and R01EB010195 is acknowledged.