Absolute MR thermometry using time domain analysis of the multi gradient-echo modulus signal

S. M. Sprinkhuizen[1], C. J. Bakker[2], and L. W. Bartels[1]

[1]Image Sciences Institute, University Medical Center, Utrecht, Netherlands, [2]Radiology, University Medical Center, Utrecht, Netherlands

Introduction Proton resonance frequency shift-based (PRFS) MR thermometry (MRT) currently is the most widely used MR temperature mapping method. The PRFS technique exploits the temperature dependency of the water proton chemical shift. Temperature changes are extracted from the phase difference between successive gradient echo MR images. Relatively long echo times in the order of the T_2^* of the tissue ($TE \geq 20$ msec) are used, to maximize SNR [1]. PRFS-based MRT has several limitations. First, it does not measure absolute temperatures but temperature changes only. Second, being a subtraction technique, it is sensitive to intrascan motion and temporal phase variations other than those related to the desired temperature effect, e.g. due to field drift, respiration induced field variations [2], etc. Third, the presence of fat hampers the applicability of the method, both because fat protons do not exhibit the temperature dependent PRF shift and because the susceptibility of fat is strongly temperature dependent [3]. This susceptibility effect is not eliminated when fat suppression techniques are employed, a fact that has often been ignored in the literature on PRFS-based MRT. Mulkern *et al.* have presented a potential solution for many of the problems inherent to PRFS MRT [4]. Instead of a gradient echo acquisition with a long echo time, these authors proposed a multi gradient-echo (mFFE) sequence using asymmetric gradient reversals to acquire multiple (n) gradient-echo images 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 at which the first gradient echo image is acquired and ΔTE the echo spacing. For each voxel, this mFFE sequence yields a densely sampled time signal containing spectral information of the substances involved. The spectral bandwidth is determined by the echo spacing, $SBW=1/\Delta TE$, the spectral resolution by the sampling time, $SR=1/(n\Delta TE)=SBW/n$. In substances containing two components of which only one has a temperature dependent resonance frequency, e.g. in tissue containing water and fat, the frequency difference Δf between the peaks in the spectrum of the mFFE signal thus provides a measure of the absolute temperature. Theoretically, Δf is not affected by local field offsets so that the mFFE technique may be expected to yield reliable absolute temperature maps, even in the presence of field drift, susceptibility effects, etc. In practice, however, the ability of mFFE to provide absolute temperature maps was not demonstrated by the authors. Hardware limitations forced the use of interleaved scanning to achieve the desired spectral bandwidth. Besides, the temperature maps were based on a frequency domain analysis of the phase evolution of the mFFE signals. In our experience, the phase spectrum is not insensitive to field inhomogeneities and susceptibility changes. In the work presented here we aim to demonstrate that the full potential of the mFFE technique can be realized by proper adjustments of the previously presented mFFE technique, including the use of a non-interleaved mFFE acquisition scheme and time domain analysis of the modulus signals instead of frequency domain analysis of the phase signal. The squared modulus signal of an mFFE sequence of a mixture with two spectral components 1 and 2 at echo time TE_i is given by: $S(TE_i)^2 = A_1^2 e^{-R^*_{2,1}TE_i} + A_2^2 e^{-R^*_{2,2}TE_i} + 2A_1A_2 e^{-(R^*_{2,1}+R^*_{2,2})TE_i}\cos(2\pi\Delta f_{12}TE_i + \Delta\varphi_{12})$ [1] with $A_{1,2}$ the effective spin density including T_1 and saturation effects, $R^*_{2,1}$ and $R^*_{2,2}$ the effective transverse relaxation rates of the components, Δf_{12} and $\Delta\varphi_{12}$ the resonance frequency difference and the phase offset difference between the two components, respectively. Our modulus-based mFFE thermometry technique retrieves the frequency difference Δf_{12}, which is related to the absolute temperature. The major benefit of the modulus based mFFE thermometry technique is its insensitivity to field inhomogeneities, due to the fact that the PRF of both components will be affected, but their frequency difference Δf_{12} will not.

Materials & Methods In vitro scans were performed on a 3T whole body system (Intera Achieva, Philips, Best, The Netherlands). Ethylene glycol (EG) was used as a test fluid for all scans, since the temperature characteristics of the chemical shift between the methylene (m) and hydroxyl (h) group in EG is well known [5]. For all experiments, Δf_{mh} was found by fitting the discrete evolution of the modulus signal in the time domain to the signal model as given in equation [2] per voxel. At 3T and T_{room}=21 ^{0}C, $\Delta f_{mh}\approx$215 Hz. In all scans therefore: $TE_1/\Delta TE$=1.8/1.8 msec, corresponding to $SBW\approx$555 Hz. The other scan parameters were: TR=100 msec; $\alpha=10^{\circ}$; acq.voxel size 1.56x1.56x10 mm^3; dynamic scan duration 13.24 sec. On our system, a maximum of 32 echoes could be acquired. The scan protocol consisted of three experiments: **1.** EG at three different temperatures, to study the ability of the modulus based mFFE sequence in yielding absolute temperature maps. **2.** 64 dynamics of EG at constant temperature to study influence of field drift on mFFE outcome. **3.** EG at constant temperature with field disturbances applied to study their influence. For all scans, the temperature was verified with optic temperature measurements (Luxtron). The mFFE output of experiment 2 was compared to 'standard' PRFS-based temperature mapping by phase image subtraction of the gradient echo images acquired at TE = 36 msec. These phase difference maps were converted into relative temperature maps.

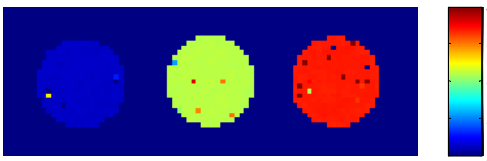

Figure 1 Three absolute mFFE temperature maps of EG at 21^{0}C (left), 31 ^{0}C (middle), and 37 ^{0}C.

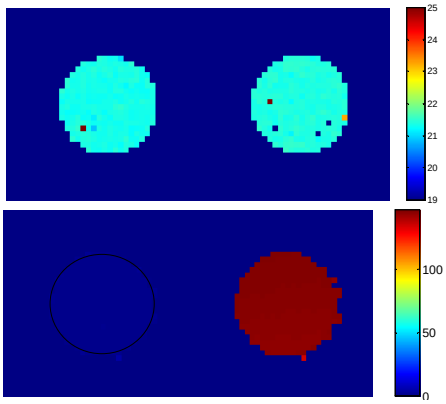

Figure 2 The top two images show absolute mFFE temperature maps of dynamic nr.2 (left) and 64 (right). Bottom two images are corresponding PRFS-based images, showing *relative* temperatures.

Results Fig.1 depicts the mFFE temperature maps of EG at three different temperatures. All mFFE based temperatures were within a 1^{0}C range of the Luxtron measurements. Fig.2 shows the influence of field drift on both mFFE and PRFS-based MRT. mFFE is not influenced by drift.The PRFS based technique however yields apparent relative temperature changes from 0 ^{0}C (dynamic 2) up to 150 ^{0}C (dynamic 64). Fig. 3 shows the insensitivity of mFFE temperature maps to field disturbances.

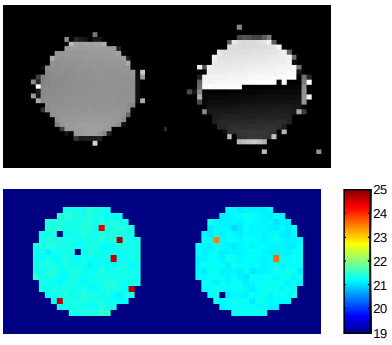

Figure 3 The top row shows phase images corresponding to the absolute mFFE temperature maps depicted at the bottom row, either with (left) or without (right) field disturbances applied. Color bar indicates absolute temperatures.

Discussion & Conclusion The experiments have shown that the modulus based mFFE technique yields absolute temperature maps, which are undisturbed by both drift and field disturbances. There are multiple ways to retrieve Δf from the mFFE signal. Besides time domain analysis of the modulus signal, also the modulus frequency domain analysis is an option. The mFFE technique can be regarded as an addition to the PRFS-based technique, in which only one gradient echo image per TR is acquired. Therefore, it can measure both absolute temperature in voxels containing both temperature independent and temperature dependent spectral components, and relative temperature in all voxels containing merely temperature dependent components. Experiments on absolute temperature measurements using the modulus based mFFE technique in vivo are currently being undertaken.

References [1] de Zwart et al. J Magn Reson B, 112,86-90 (1996) [2] S.M. Sprinkhuizen et al. 6th Interventional MRI Symposium, Leipzig, 2006, nr.V-40 [3] Stollberger et al. Magn Reson Imaging, 1998 Jan-Feb;8(1):188-96 [4] Mulkern et al. J Magn Reson, 1998 Mar-Apr;8(2):493-502 [5] Amman et al. J Magn. Reson, 1982, 46, 319-321.