Chemically selective asymmetric spin-echo EPI phase imaging for internally referenced MR Thermometry

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Introduction:
The proton resonance frequency shift (PRF) MR thermometry method is inherently very sensitive to remaining fat signal and to magnetic field perturbations in time [1]. These may be due to field drift, shim instability, gradient heating, or susceptibility changes in surrounding tissue, and must be monitored to ensure accurate temperature measurement. Previous studies have either a) assumed that a reference region has constant temperature and used its frequency change as a correction, or b) measured as a calibration the temperature of a nearby tissue region both with a thermometer and MR Thermometry [2], or c) used the frequency change of an almost temperature-independent reference substance (e.g. fat or oil) mixed with the water to correct the temperature-dependent water proton frequency change. This can be performed, for instance, with spectroscopic methods (where NAA can be used) or by alternating RF saturation or inversion of the unwanted signal [3].
Here we implemented a novel spin-echo EPI sequence that can acquire a time series of phase images of different chemically-shifted protons at the same slice positions. This enables highly accurate MR Thermometry, in which an internal reference substance is used to correct each voxel independently. We employed the efficient chemical-shift-selective spin-echo (SE) technique introduced by Ivanov [4], which uses different slice-select gradient amplitudes for excitation and refocusing RF pulses, to image only the on-resonant species (figure 1). In order to retain phase sensitivity, we used an asymmetric EPI readout.

Methods:
Dimethyl sulfoxide (DMSO) was used as a reference species. The six protons of DMSO have a single resonance peak shifted by -2 ppm relative to water protons. First the relative thermal coefficient of water with respect to DMSO was experimentally determined to be -0.0096 ppm/°C (similar to the thermal coefficient of pure water) using a temperature-calibrated 600MHz spectrometer (Bruker, BioSpin). Imaging experiments were performed on a 7 Tesla Siemens whole body scanner. The sequence used, a modification of the Ivanov approach to acquire chemical-shift-selective phase images [4], is shown in Figure 1. The centre in k-space of the EPI readout is shifted away from the SE position. The sequence was first tested on a phantom containing spatially separated water and DMSO compartments. Next, a heating experiment was performed using a DMSO and water mixture, heated using hot air and monitored with an inserted Luxtron (Lumasense) temperature sensor. This method of phantom heating induces an internal magnetic field shift, because the magnetic susceptibility of air changes with temperature [5]. To achieve good separation of the two chemical species, using the same slice thickness, the excitation slice-select gradient was 25 mT/m and the refocusing gradient was 5 mT/m. During the experiment we alternately acquired DMSO and water images at the same slice position by switching the scanner reference frequency between those of DMSO and water (TE = 25 ms; k-space centred at 45 ms → effective echo time TE_{eff} = 20 ms; TR = 1 s; bw = 1302 Hz/Px; phase partial Fourier = 6/8; resolution 128×128; voxel size: 2×2×1.4 mm^3). The water phase images were then pixel-wise corrected using the DMSO images and subtracted from a reference image.

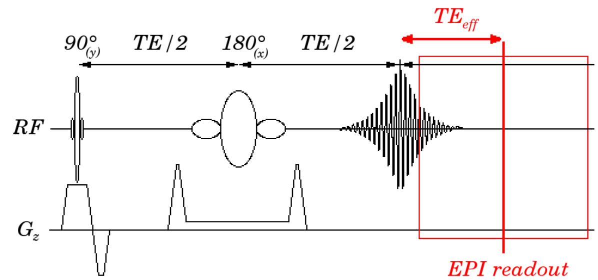

Figure 1: asymmetric SE EPI sequence with different gradient amplitudes for chemical-shift-selective phase imaging.

Results:
Figure 2 shows magnitude images of the phantom with physically separate DMSO and water compartments. The approach shows excellent suppression of either the water signal or the DMSO signal, depending on the resonance frequency used. Figure 3 shows the results of the Hot Air experiment with the water/DMSO mixture. The blue circles display the measured phase temperature of a 9 voxel ROI positioned at the Luxtron sensor. These uncorrected phase temperatures show the effect of the expected phase change due to the surrounding hot air, and also a small scanner field drift. After correction using the DMSO reference, the corrected data points (black circles) show a standard deviation of 0.2°C across the ROI and a maximal deviation from the Luxtron sensor temperature of 0.3°C.

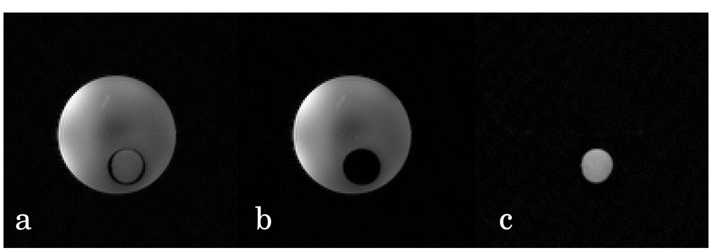

Figure 2: Phantom with separate water and DMSO compartments. a) standard SE; b) SE with Ivanov method at water resonance frequency, suppressing DMSO; c) SE with Ivanov method at DMSO resonance frequency, suppressing water.

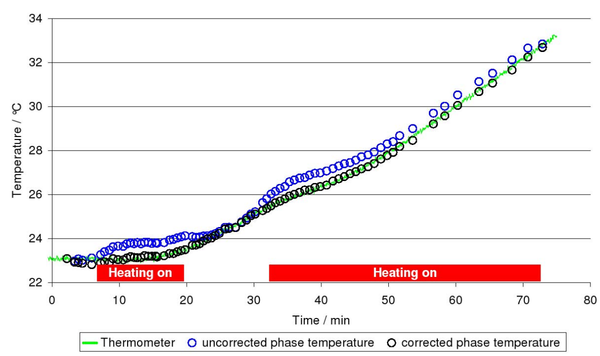

Figure 3: The mixed water/DMSO phantom is heated with hot air and the measured temperatures inside the phantom are plotted.

Conclusion:
The new chemically selective SE EPI sequence is able to suppress reliably either the water signal or the reference signal, and this suppression is highly insensitive to B_1 and B_0 inhomogeneity. This approach can correct accurately for temporal scanner instabilities and susceptibility changes of the surrounding environment. Excellent agreement within 0.3°C was achieved between the temperature of the phantom measured using phase images and the Luxtron sensor. Fat in tissue is also a feasible reference substance, and because it has a larger chemical shift than DMSO from water, it needs less difference in slice-select gradients.

References:
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