Improved MR thermometry in the presence of non-water proton signals

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Purpose: Sensitivity of the water proton resonance frequency (PRF) to temperature changes has been exploited for monitoring and control of thermal therapies[1]. Recently its use for measuring local energy deposition associated with RF transmission was suggested[2]. This is particularly important for parallel RF transmission (pTx) at high field, where energy deposition may be highly non-uniform. We developed an inexpensive, stable, and easy-to-produce phantom material, of which dielectric properties can be tuned to match various tissue types at MRI-relevant RF frequencies[3]. Its one notable drawback is the high sucrose content, which precludes the use of conventional PRF-based MR thermometry[4]. Here we present a fitting-based method that allows measuring changes in water-PRF, and thus temperature, in the presence of known nuisance signals, allowing for reliable MR-thermometry in this phantom material.

Methods & Results: Temperature dependence of PRF is the result of a proton's chemical environment. Significant signal from non-water protons (e.g. lipids[5]) interferes with the water signal and depends on both echo time and absolute temperature. If nuisance signal spectral distribution is known however, water-PRF changes can still be measured with the nuisance signal serving as an internal reference[6]. We developed a non-linear least squares fitting algorithm of the complex signal evolution as a function of echo time in multi-gradient-echo (MGRE) data, based on the following signal evolution model:

$$S(t) = \left(A_w \cdot e^{\left(i\cdot\omega_w\cdot t - R^*_{2,w}\cdot t\right)} + A_{nui}\cdot S_{nui}(t)\cdot e^{\left(i\cdot\omega_{nui}\cdot t - R^*_{2,nui}\cdot t\right)}\right)\cdot e^{\left(i\cdot\phi_g\right)}$$

$S(t)$ is the complex signal as a function of echo time t, $S_{nui}(t)$ the unattenuated temperature-independent nuisance signal evolution (here the combined signal from all 32 resonances in sucrose[7]). We fit 7 parameters: decay constants $R^*_{2,w}$ & $R^*_{2,nui}$; amplitudes A_w & A_{nui}; frequencies ω_w & ω_{nui}; phase offset ϕ_g at t=0. Subscripts $_w$ and $_{nui}$ identify the water and nuisance (sucrose) pool, respectively.

Calibration experiments were performed at 7 T (2×2×2 mm^3; 63 echoes; 90 s·vol^{-1} acquisition time) on different gel types to determine the water-PRF temperature dependence α. At first (Fig. 1) the two agar gels described in [3] were used, mimicking brain (ε=48; σ=0.63 S·m^{-1}, phantom B[3]) and muscle (ε=59; σ=0.79 S·m^{-1}, phantom A[3]). They were placed in a warm water bath after which cool-down was monitored with the proposed method. OpSens temperature probes were used as a reference. PRF temperature dependence α was found to be -0.0090±0.0003 ppm·K^{-1}, independent of sucrose and salt concentration and in line with literature values for tissue[8].

As measurements with gelatin-based samples indicated a dependence of α on gelling agent, a second set of experiments (7 T; 2×2×2 mm^3; 28 echoes; 1.20-ms spacing; 60 s·volume^{-1}) used muscle-mimicking phantoms with agar replaced by gelatin (0.5-4.5%). Samples with 1.5% agarose and no gelling agent were also included. Because of the low melting point of gelatin these samples were placed in ice water and the warm-up to room temperature was monitored. Surprisingly, α was about 30% reduced in gelatin-based phantoms (Fig. 2), independent of gelatin concentration. MR spectroscopy data on the 4.5% concentration yielded α = -0.0061 ppm·K^{-1}[9], consistent with these findings.

Fig. 3 shows application of the method to monitor heating with use of an in-house developed spine coil (8-channel receive, 2-channel dipole transmit[10]). Off-resonance RF irradiation (equivalent to 32.4 W continuous power) was performed for 10 min on a 60×43×11 cm^3 muscle-mimicking agarose gel phantom. Results are in line with simulations (not shown) for this dipole transmit coil array.

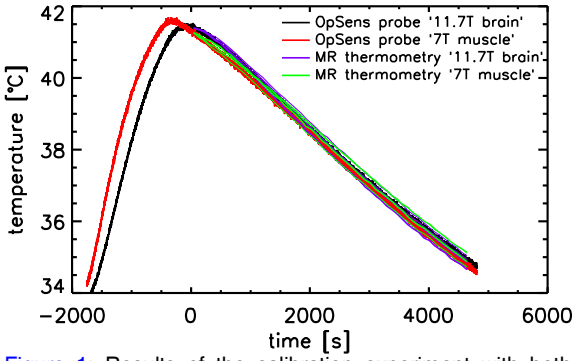

Figure 1: Results of the calibration experiment with both 11.7 T, brain-like and 7 T, muscle-like gels[3]. MR data are from 4 voxels surrounding each fiberoptic probe.

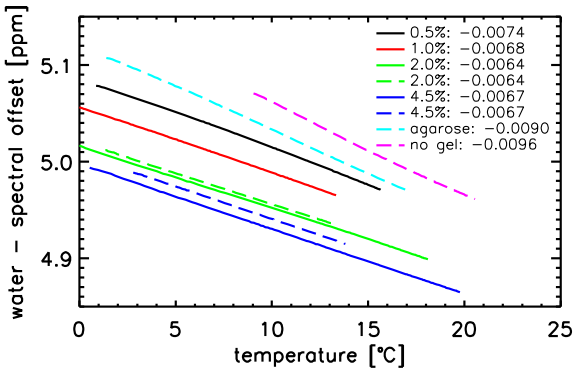

Figure 2: Results of the second set of experiments using gelatin-based gels. Scans from two different days are shown (solid vs. broken lines). An agarose gel and a sample without gelling agent were included for comparison. Values for PRF temperature dependence α are in ppm·K^{-1}.

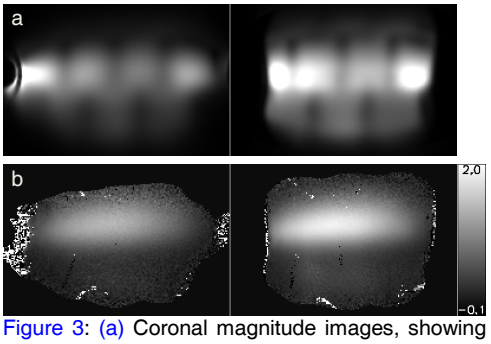

Figure 3: (a) Coronal magnitude images, showing evidence of signal dropout between receive elements; (b) MR thermometry after 10-min RF heating, showing temperature change in K.

Discussion: Use of sucrose-based gel phantoms for MR thermometry requires careful separation of water and non-water proton signals, here based on modeling the signal evolution of MGRE data, allowing RF heating-related changes in water PRF to be determined reliably. Sucrose PRF signals serve as an internal frequency reference, e.g. to compensate for the effects of field drift. The method requires complex signal data from at least 4 echoes and an accurate spectral description of the nuisance signal. Low flip angle MGRE can be effectively used for MR thermometry without significant additional RF-power deposition, while irradiation at very large offset frequency introduces substantial SAR-related heating without affecting the MR signal. In theory, the proposed method allows for measurement of absolute temperature, but water PRF for a given temperature depends on gel type and concentration (reproducibly, see Fig. 2), possibly as a result of spin exchange. Resolving this issue will require further study.

References: [1]de Senneville, EurRadiol 2007(17):2001; [2]Cloos, ISMRM 2013:286; [3]Duan, MedPhys 2014(10):102303; [4]Ishihara, MagResonMed 1995(34):814; [5]de Zwart, MagnResonMed 1999(42):53; [6]Sprinkhuizen, MagnResonMed 2010(64):239; [7]http://www.hmdb.ca/spectra/nmr_one_d/1293; [8]McDannold, IntJHyperthermia 2005(21):533; [9]Deniz, ISMRM "Safety in MRI" 2014, Washington, DC; [10]Duan, ISMRM 2014:316