Proton-Resonance Frequency Shift MR Thermometry is Affected by Changes in the Electrical Conductivity of Tissue

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Introduction: The proton-resonance frequency (PRF) shift method of MR thermometry provides an easy and practical means of quantitatively monitoring in vivo temperatures for MR-image guided thermal-coagulation therapy. In this study, we identify a potential source of variation in the PRF-shift method of thermometry [1] that manifests as a constant increment in phase-shift per unit change in temperature that is independent of the echo-time (TE) setting. We propose that this phase-shift offset arises from thermally-induced changes in the electrical conductivity and permittivity of the material. To this end, we demonstrate that the apparent PRF-thermal coefficient can be overestimated by as much as 28% in a heating experiment of freshly excised cow liver. A simple method of overcoming this phase-shift offset is presented.

Theory: With the PRF-shift method of thermometry, the phase-shift sensitivity or thermal coefficient is generally modelled as:

$$\Delta \phi / \Delta T = \gamma \cdot B_0 \cdot \alpha \cdot (360°/\text{cycle}) \cdot TE$$

where \(\gamma\) is the gyromagnetic ratio for \(^1H\) nuclei, \(B_0\) is the field strength, and \(\alpha\) is the apparent PRF-thermal coefficient containing contributions from changes in the electron screening constant and magnetic susceptibility [2,3]. In a conductive material, a transmitted \(B_1(t)\) field will undergo amplitude attenuation and phase retardation, giving rise to a variation in tip angles and phase over the object [4]. In particular, the spatial nature of the phase variation in the MR image will depend on the material properties and the imaging coil(s) used to transmit and receive the RF signal. For a linearly-polarized field this phase variation can be characterized by a wavenumber, \(k\), given by:

$$k = \omega / (2\epsilon\mu) \left( \sqrt{1 + (\sigma / \omega \epsilon)}^2 + 1 \right)$$

where \(\epsilon\) is the permittivity, \(\mu\) is the permeability, and \(\sigma\) is the electrical conductivity of the material. Temperature-induced changes in the material's electrical conductivity and, to a lesser extent, permittivity will result in changes in the wavenumber and, thus, the phase-retardation of the \(B_1(t)\) fields. These changes from the reference condition will deposit phase shifts that are independent of the spin-evolution waiting period \(TE\), thus rendering the model in Eq.1 incomplete for estimating temperatures.

Methods and Materials: Temperature-induced phase shifts were measured in 2% agar-filled tubes that were immersed in a 1.8 L container through which either pure water, 20 mM NaCl, 60 mM NaCl, 20 mM MnCl\(_2\), or 60 mM MnCl\(_2\) solution was heated and circulated. The volume occupied by the agar gel-filled tubes was only 10% of the total capacity, so that any phase retardation effects would be primarily due to thermal changes in the properties of the circulating solution. A uniform-heating experiment of a large volume (0.7 L) of water was circulated and removed prior to imaging so as to exclude its effect on the phase retardation. All imaging was performed on a 1.5 T MRI system (GE SIGNA) using a standard-quadrature head coil. Phase-shift ROI measurements were obtained from multiple TE settings of 6,7,8,10, and 15 ms using a spoiled gradient-echo sequence (SPGR). A linear fit was made to the resultant phase-shift data as a function of temperature over the range of 20°C to 80°C to obtain the apparent PRF-thermal coefficient. The phase-shift thermal-coefficient offset was determined by extrapolating the multi-TE results to the \(TE = 0\) intercept (Fig.1).

![Figure 1: The calculated phase-shift temperature sensitivity \((\Delta \phi / \Delta T)\) as a function of the \(TE\) setting in a 9% agar gel sample, using a 20 mM MnCl\(_2\) circulating solution. The above plot suggests the presence of a phase-shift thermal-coefficient offset of -0.29°C. A method of overcoming this apparent offset in determining the PRF-thermal coefficient is indicated using two \(TE\) settings.](https://example.com/figure1)

Results: As seen along the vertical axis of Fig.2, a range of phase-shift offsets were observed in the solutions studied. In the excised liver tissue, an offset of -0.33°C was found, which would have caused an overestimation of the PRF-thermal coefficient by 28%, had only data from the \(TE\) setting of 6 ms been used. Good correlation can be seen between the experimentally-measured phase-shift thermal-coefficient offsets and the modelled wavenumber-thermal coefficients, among the different materials studied (Fig.2).

Conclusion: A \(TE\)-independent offset has been observed in the PRF-shift method of MR thermometry which could lead to erroneous temperature estimates if neglected. We propose that thermally-induced changes in the electrical conductivity and permittivity alter the phase retardation of the transmitted and received \(B_1(t)\) fields and are responsible for the phase-shift thermal-coefficient offsets. We believe that an understanding of this phenomenon may help resolve the discrepancies in the PRF-thermal coefficient reported in the literature.