Are multiple phase references needed for phase correction in proton resonance frequency shift thermometry?

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Introduction

In proton resonance frequency (PRF) shift MR thermometry, temperature changes are measured through phase changes. A thermal coefficient of -0.01 ppm/°C is used to relate phase change to temperature change. The uncertainty in the measured temperature has three contributions: uncertainty in the thermal coefficient, phase noise, and uncertainty in the phase changes of a thermally insulated reference used to track magnetic field changes. The uncertainty in the thermal coefficient is at least 5% [1] and may be as large as 30% depending on the method of heating and temperature dependence of tissue electrical conductivity [2, 3]. The phase noise is related to the reciprocal of the signal-to-noise of the magnitude image [4]. The reference phase is not a constant but drifts in time. In the past, this drift has been attributed to receiver electronics and a normally specified linear magnetic field drift; so a single phase reference phantom has been used [1]. More recently, El-Sharkawy and Atalar [5] have demonstrated spatial and temporal magnetic field variations resulting from magnet temperature changes from gradient and RF heating. In their experiment, they intentionally heated the magnet by running a gradient intensive sequence for one hour. They concluded that at least three non-collinear phase references are needed for phase correction in PRF thermometry. In this work we evaluate the necessity for multiple phase references in the context of the overall uncertainty in temperature measurement.

Materials and Methods

All experiments were performed on a Philips 3.0 T Intera system (Philips Medical Systems, Best, NL). The phase of a mineral oil phantom was measured with a pulse sequence that would normally be used for temperature mapping every minute for 110 minutes. An oil phantom was used because the resonance frequency of lipids does not depend on temperature; hence, phase or frequency drifts measured were the result of magnetic field changes. The thermometry sequence was a 2D-multislice T1 weighted field echo segmented EPI with FOV = 350 x 350 mm, 3 slices in orthogonal directions of 5 mm thickness, acquisition 256 x 246, reconstruction 256 x 256, TR = 31 ms, TE = 20 ms, flip angle 30°, 9 k-space lines/TR, sense 2, and 3 s per 3 slices. To measure realistic magnetic field variations, the scanner was not heated with gradient intensive sequences beforehand. Phase difference maps were obtained by subtracting the phase map at a specified time from the initial phase map. Field gradients along the X and Y directions were obtained from linear fits in axial images; field gradients along the Z direction were obtained from linear fits in coronal images.

A thermal coefficient of -0.01 ppm/°C has been validated at 3 T by measuring the phase and temperature simultaneously of a gelatin phantom upon cooling. The temperatures of the heated gelatin and reference gelatin were measured with a fiberoptic sensor (Luxtron, Santa Clara, CA).

Results

Figure 1a shows a typical magnetic field drift of 0.0601 ± 0.0004 ppm/h associated with the above thermal sequence. Figure 1b shows the field variation that developed in the Y direction after running the thermal sequence for 110 minutes. Table 1 lists the linear fits to the field gradients. The errors are standard errors of the mean. Statistical significance is taken at the 5% level. No significant gradient developed in the X direction. Z gradients tended to but did not achieve significance. Only Y gradients achieved significance by 90 minutes.

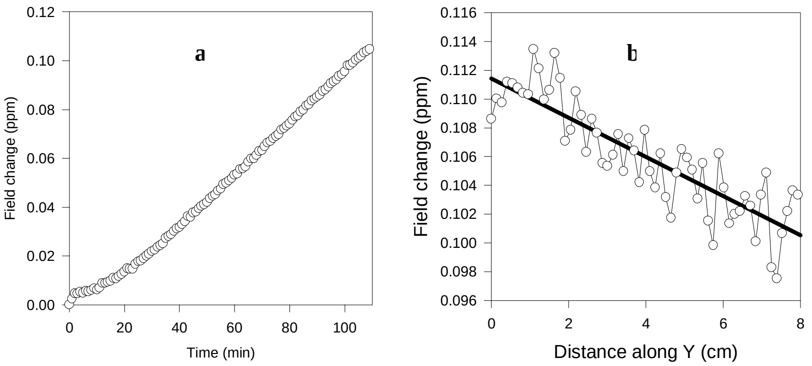

Figure 1: (a) Magnetic field drift during MR thermometry; (b) Magnetic field changes in Y direction after running the thermal sequence for 110 min. Line is a least squares fit.

Discussion

Magnetic field variations resulting from magnet heating depend on the pulse sequence, repetition frequency of the sequence, and duration of the sequence. In intermittent thermometry at 3 T with the above sequence, these variations are small. The error in temperature measurement from these field variations also depends on the distance between the phase reference and heated region. At the largest measured field gradient, 0.0014 ppm/cm, with a phase reference located 15 cm away from the heated region, the error in the measured temperature neglecting this field variation would be 2.1°C. In monitoring thermal ablations, this error is insignificant; thus, a single phase reference is sufficient. However, for applications like drug delivery and control of gene expression, where tight control of temperature over extended periods may be required, multiple phase references to take into account spatial variations in the magnetic field drift will be needed if the phase references are located far from the heated region.

Table 1: Mean and standard error of the mean (in parentheses) induced magnetic field gradients in X, Y, and Z directions in 10^{-4} ppm/cm as function of duration of thermometry sequence

Time (min)	X	Y	Z
30	2.2(0.5)	5.7(0.7)	3.0(1.3)
60	0.3(0.5)	8.0(0.8)	2.0(1.4)
90	0.7(0.4)	12.4(0.7)	6.1(1.5)
110	1.1(0.4)	14.2(0.8)	9.8(1.3)

References

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