Monitoring and correcting spatio-temporal variations of the MR scanner’s static magnetic field

Abstract  The homogeneity and stability of the static magnetic field are of paramount importance to the accuracy of MR procedures that are sensitive to phase errors and magnetic field inhomogeneity. It is shown that intense gradient utilization in clinical horizontal-bore superconducting MR scanners of three different vendors results in main magnetic fields that vary on a long time scale both spatially and temporally by amounts of order 0.8–2.5 ppm. The observed spatial changes have linear and quadratic variations that are strongest along the z direction. It is shown that the effect of such variations is of sufficient magnitude to completely obfuscate thermal phase shifts measured by proton-resonance frequency-shift MR thermometry and certainly affect accuracy. In addition, field variations cause signal loss and line-broadening in MR spectroscopy, as exemplified by a fourfold line-broadening of metabolites over the course of a 45 min human brain study. The field variations are consistent with resistive heating of the magnet structures. It is concluded that correction strategies are required to compensate for these spatial and temporal field drifts for phase-sensitive MR protocols. It is demonstrated that serial field mapping and phased difference imaging correction protocols can substantially compensate for the drift effects observed in the MR thermometry and spectroscopy experiments.

Keywords  Magnetic field · Field homogeneity · Magnet stability · Field mapping · MR thermometry

Introduction

The stability and homogeneity of the main magnetic field are important factors that directly impact the accuracy of MR experiments that are phase sensitive. Phase-based proton-resonance frequency (PRF) MR thermometry measurements are particularly susceptible to underlying field variations [1]. Field homogeneity and stability affect the signal-to-noise ratio (SNR) and resolution in MR spectroscopy. Two major sources of frequency drifts have been identified [2]. First, oscillatory phase drifts that correlate with air-conditioning cycles in the equipment electronic room. These are greatly reduced by advances in receiver electronics. Second, there is the normal drift in the main magnetic field that falls within the magnet’s specifications. This temporal drift is currently treated as spatially homogenous [3]. For PRF thermometry correction primarily involves subtracting the phase of a reference image from the temperature-dependent phase. These also accounts for spatial phase variations due to susceptibility effects [4]. Although the possible existence of phase variations attributable to the main static magnetic field that are both temporal and spatially dependent...
has been noted, we have found no accounts of the nature, magnitude, or extent of such variations.

Here we show that magnetic field variations are induced by, and directly correlated with, the hardware stress of the MRI system. In particular, the evidence suggests that eddy currents caused by switching gradients result in heating of resistive parts of the MR scanner. We find that the changes in field vary both spatially and temporally in a working, state-of-the-art horizontal-bore clinical MRI systems made by each of GE (1.5 T), Siemens (1.5 T) and Philips (3 T). The observed spatial variations have both linear and quadratic terms that are especially significant in the z direction. We hypothesize that thermal perturbations alter the passive shimming, which in turn results in spatial and temporal field variations. The consequence of such variations on the accuracy of PRF thermometry is demonstrated. The degradation of field homogeneity is manifested as both frequency shifts and spectral line-broadening in single-voxel spectroscopy of a phantom and of a human brain in vivo. Two field (phase) compensation schemes are presented that can successfully correct for the errors produced by the magnet’s spatial/temporal drifts in MR thermometry and spectroscopy experiments. We conclude that serial online or offline field/phase-variation compensation strategies may be essential to the accuracy, stability, and quality control of such experiments.

**Theory**

Measuring the magnetic field

In a gradient echo (GR) or a spoiled gradient echo (SPGR) MR experiment the sampling/echo acquisition time is small compared to T2 [5]. If the temperature of the imaged subject is not varying, the subject is stationary, a time is small compared to T2 [5]. If the temperature of the MRI system. In particular, the evidence suggests that eddy currents caused by switching gradients result in heating of resistive parts of the MR scanner. We find that the changes in field vary both spatially and temporally in a working, state-of-the-art horizontal-bore clinical MRI systems made by each of GE (1.5 T), Siemens (1.5 T) and Philips (3 T). The observed spatial variations have both linear and quadratic terms that are especially significant in the z direction. We hypothesize that thermal perturbations alter the passive shimming, which in turn results in spatial and temporal field variations. The consequence of such variations on the accuracy of PRF thermometry is demonstrated. The degradation of field homogeneity is manifested as both frequency shifts and spectral line-broadening in single-voxel spectroscopy of a phantom and of a human brain in vivo. Two field (phase) compensation schemes are presented that can successfully correct for the errors produced by the magnet’s spatial/temporal drifts in MR thermometry and spectroscopy experiments. We conclude that serial online or offline field/phase-variation compensation strategies may be essential to the accuracy, stability, and quality control of such experiments.

**MR thermometry**

We posit that in a GR MR experiment temperature changes of the equipment may result in variations in the field homogeneity. We therefore monitor the magnet homogeneity using either or both of the above methods. The apparent temperature change due to heating,

\[
\Delta T(r, t_{2} - t_{1}) = \frac{\Delta \phi(r, t_{2} - t_{1}, \text{TE})}{-\alpha \times \text{TE} \times \gamma \times B_{0}}
\]

with \(\alpha = -0.01 \text{ ppm/ } ^{\circ} \text{C} \) [9,10], will be superimposed on any magnetic field variations. To compensate for magnetic field variations over the imaged sample volume, we either actively re-shim the magnetic field using the scanners shim gradients [11] or use offline phase-variation compensation.

2D field variation analysis and correction

The spatial variation of the field in planar image acquisitions quantified via Eqs. (4) and (6) for Methods A and B respectively, is quantified and corrected using a two-dimensional (2D) quadratic model. The same model is used for field changes during MR thermometry experiments [8]. The spatial variation of the field is thereby

\[
\Delta \phi(r, t, \Delta \text{TE}) = \gamma \Delta B_{0}(r, t) \text{TE} - \gamma \Delta B_{0}(r, t) \text{TE}\]

Therefore,

\[
\Delta B_{0}(r, t) = \frac{\Delta \phi(r, t, \Delta \text{TE})}{\Delta \text{TE} \times \gamma}
\]

where \(\Delta \phi\) is the difference in phase, and \(\Delta \text{TE} = \text{TE}_{2} - \text{TE}_{1}\). If we reasonably assume that the main magnetic field, and consequently the inhomogeneity term, stays constant during \(\Delta \text{TE}\), then we may use this method (method A) to measure static field maps and/or to calculate shim values. By measuring \(\Delta B_{0}\) at different time points \((t_{1}, t_{2}, \text{etc.})\) over time frames of minutes or hours, the longer-term temporal field variations are determined:

\[
\Delta B_{0}(r, t_{2} - t_{1}) = \Delta B_{0}(r, t_{2}) - \Delta B_{0}(r, t_{1})
\]

Alternatively, we can utilize the phase difference in images (PDI) that are acquired with the same TE at different time instances to account for field variations (method B):

\[
\Delta \phi(r, t_{2} - t_{1}, \text{TE}) = \gamma \Delta B_{0}(r, t_{2} - t_{1}) \text{TE}
\]

\[
\Delta B_{0}(r, t_{2} - t_{1}) = \frac{\Delta \phi(r, t_{2} - t_{1}, \text{TE})}{\gamma \times \text{TE}}
\]