Combination of gradient echo and chemical shift imaging allows MR thermometry over long timescales

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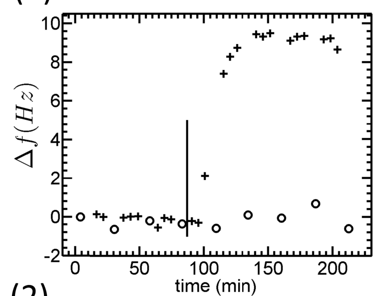
Introduction. Induced Focal Cerebral hypothermia, or brain cooling, has been used to achieve neuroprotection in many neurological insults such as cardiac arrest, traumatic brain injury, and stroke.[1] The effectiveness of a given cooling strategy can be assessed by non-invasive measurements of brain temperature during the treatment. Maps of relative temperature changes over the duration of a cooling treatment can be obtained using water proton resonance frequency (PRF) shift thermometry.[2,3] This method is based on the fact that the chemical shift of water changes linearly with temperature by approximately -0.01 ppm per °C. This shift can be measured by detecting the phase associated with each voxel of an image obtained with a gradient echo sequence (GRE). By comparing the phase difference between two consecutive scans it is possible to estimate the temperature change that occurs between the scans. Such calculations are based on the assumption that the change in the frequency due to the change in the temperature is large relative to the change in frequency due to the drift in the magnetic field strength. Although this assumption is valid when the scans are performed in rapid succession, it is likely to be violated in brain cooling treatments when temperature changes are sought over times scales in the range of 20-60 minutes. Accurate temperature measurements over these time scales require that the field drift be characterized. This can be done by measuring the chemical shift of a species that is not sensitive to temperature, such as N-acetylaspartate (NAA), typically measured using chemical shift imaging (CSI).[4] Although the CSI scans are time intensive and provide less spatial resolution than GRE scans, they can provide information about the magnetic field that is necessary for a long-term MR thermometry experiment. Here, we demonstrate long term thermometry experiments obtained by a series of GRE scans, interspersed with intermittent CSI scans that are used to characterize the field.

Experimental. Our measurements consist of a series of GRE scans, performed every 4 minutes, interspersed with CSI scans, performed after every 3 GRE scans. Shimming is performed before the initial scan and remains unchanged for all subsequent scans. The CSI scans are 2D spin echo, 4 x 4 voxels over a region of interest (ROI) that is 55 x 55 mm, with a thickness of 10 mm, TR = 2400 ms, TE = 30 ms, BW = 1000 Hz, and 2048 points acquired with weak water suppression. A spatial Hamming filter is used and the spectra are averaged over three measurements for a scan time of 7 min and 50 sec. From the spectra obtained from each pixel we calculate the locations of the water and NAA peaks by using a Savitzky-Golay filter to smooth the magnitude values of each spectrum, fitting the resulting function with cubic spline and then finding the maximum of the smoothed function. We also performed 3D GRE scans with a field of view of 220 x 110 mm, 8 slices of 5 mm thickness, TR = 60 ms, and TE = 20 ms for a total scan time of 45 sec. The GRE scans are centered and orientated such that the ROI from the CSI scan falls within the center of the field of view of the center slices. Each large voxel of the CSI coincides with 8x8x2 voxels of the GRE scans. Validation experiments on a water phantom at thermal equilibrium indicate that the frequency of GRE and CSI scans is sufficient to characterize normal magnetic field drift to within approximately 1 Hz.

We measure the cooling of a phantom consisting of 10 mM NAA in phosphate buffer saline solution, pH 7.5. The phantom is contained within a plastic bottle that is immersed in a homemade water-filled temperature bath made of PVC. The water in the bath is circulated through inlet and outlet tubing by a circulating temperature-control unit equipped with an electric pump. A fiber optic temperature probe is inserted into the PVC temperature bath to measure the temperature of the circulating water. The PVC unit is placed inside a Siemens 3 T Allegra MRI scanner, and the circulating bath is placed outside of the room containing the scanner.

(1)



(2)

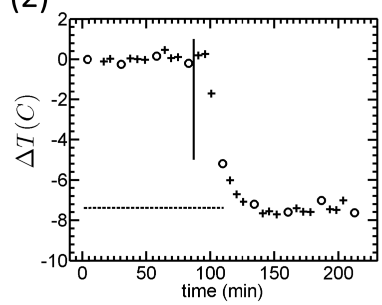


Fig. (1) *Change in frequency measured during CSI experiment from chemical shift of NAA (circles) and from GRE scan (pluses).* **Fig (2)** *Temperature change measured by CSI (circles) and GRE (pluses). The solid lines show time for change of set temperature of bath and the dashed line shows the final temperature drop measured by the fiber optic probe. Data in both figures are from CSI collected in one voxel and data from GRE are averaged over the corresponding 8x8x2 voxels.*

Results. Initially the temperature of the bath was fixed and the system was allowed to equilibrate while the measurement fiber optic probe remained steady at 37.7 ± 0.1 ^{0}C. We then lowered the set temperature of the bath and allowed the system to equilibrate to 30.3 ± 0.1 ^{0}C. The temporal variation of the field strength measured by the CSI scans is small relative to the change in frequency measured by the GRE scans (Fig. 1). This implies that we are able to calculate a temperature change without correcting for changes in the field strength. We test this hypothesis by averaging the temperature measurement over the 8x8x2 voxels of the GRE within each large voxel of the CSI, and comparing the temperature that is measured from the difference between the water peak and the NAA peak in the CSI experiment. As expected, results from the two measurements are consistent (Fig.2).

Conclusions. In PRF shift thermometry, GRE scans provide fast, high-resolution estimates of temperature changes, but can be confounded by changes in the magnetic field. Supplementing GRE scans with drift-insensitive CSI scans provides an accurate characterization of field drift that is needed to separate field and temperature effects in GRE phase estimations over long time scales. Although field drift is negligible in this experiment, in earlier data sets (not shown) there was significant field drift due to more frequent GRE scanning. The temperature monitoring with CSI will provide critical quality control or allow for correction of field drifts in future data sets where the duration of the experiment may be longer or the accuracy of measurements needs to be increased. Provided that the variations in the field are sufficiently gradual in time and space, the CSI data may be interpolated in time and in space to correct the GRE data, thereby providing high resolution temperature mapping over extended timescales.

Acknowledgement. We thank the Beckman Institute at University of Illinois Urbana-Champaign for financial support.

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