# Improved Proton NMR Thermometry by Field Inhomogeneity Correction Post-Processing

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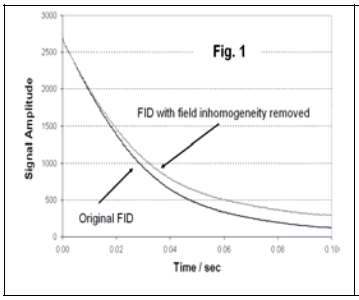
**Introduction:** Proton ($^1$H) NMR (PNMR) thermometry has been applied as a non-invasive brain temperature quantification method for over a decade. A change in brain temperature can be determined from the change in the $^1$H resonance frequency of water in region of interest [1-4]. Actual brain temperature can be quantified by measuring frequency difference between the temperature dependant water resonance frequency and a temperature independent metabolite resonance frequency, most often that of NAA [5-7]. The PNMR technique uses a robust linear correlation between water $^1$H resonance frequency and brain temperature. However, the method is limited by resonance frequency estimation error as aggravated by the low SNR of metabolite signals as well as the presence of magnetic field inhomogeneities. We propose an improved data processing method exploiting a *post facto* magnetic field inhomogeneity correction *via* additional field map MR acquisition. A temperature calibration performed on rat brain *in vivo* with an 11.74T MR scanner shows substantially improved accuracy.

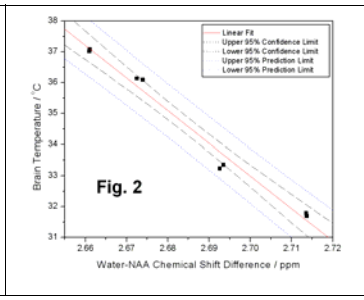
**Theory and Methods:** The detailed theory and algorithms for field map *post facto* magnetic field inhomogeneity correction have been discussed previously [8, 9]. Briefly, the original total FID signal $S(t)_{measure}$ can be represented as a product of the "natural signal" $S(t)$ that would exist in the absence of macroscopic field inhomogeneities, multiplied by a function $F(t)$, representing signal decay (dephasing) caused by macroscopic field inhomogeneities $B(\vec{r})$ (residual inhomogeneities that are not removed by shimming process): $S(t)_{measure} = F(t) \cdot S(t)$, where $F(t) = \int \exp\{-i\gamma B(\vec{r})t\} d\vec{r}$. Introducing the $F(t)$ function recovers the natural signal $S(t)$, substantially improving signal linewidth and shape.

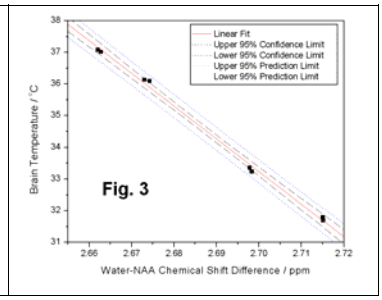
Temperature calibration employed single voxel MRS simultaneously with direct brain temperature measurement *via* fiber-optic probe. Rats were anesthetized with 1.2% isoflurane (n=3). MRS LASER sequence [10] parameters were: 4000Hz bandwidth, TR=1.6s, TE=75ms, 512ms acquisition time, 3×3×3 mm$^3$ voxel size. During the calibration experiment, the subject's body was cooled slowly from 37.5 °C to 30 °C by controlling the temperature of water circulating in a pad under its abdomen. A total of 4 data sets were obtained in a 3-hour period. Each data set consisted of one field map and two LASER spectra (each averaged 100 times for increased SNR). The high resolution (0.25x0.25x0.4 mm$^3$) field map was obtained with a 3D Gradient Echo double-echo sequence employing GE times 5ms and 14.2ms and TR of 23ms. Field map data were loaded into MATLAB and the F function was calculated for the region of the corresponding MRS voxel. The corrected FID was then loaded into MestReC software (Mestrelab Research, Spain) for resonance frequency determination. For comparison, we also processed data in the same program without the field map correction.

**Results and Discussion:** An example of the FID signal with and without correction for field inhomogeneities is presented in Fig. 1. The corrected (natural) FID shows significantly lower decay rate as compared to the original FID. When comparing spectra in frequency domain (data not shown), the linewidths (LW) of both the water and NAA peaks are markedly decreased after correction: the water LW decreased from 13.1Hz to 6.0Hz and the NAA LW from 19.5Hz to 5.4Hz. The effect of field inhomogeneity correction on brain temperature vs. resonance frequency calibration is shown in Fig. 2 and 3 for one subject. The significantly tightened correlation with field map correction more than doubles the accuracy of brain temperature estimation (± 0.3-0.4 °C). Considering data from all three subjects ($R^2$ = 0.99): $T_b - 37 = (-105.23 \pm 2.14) \times (f_{H2O\text{-}NAA} - 2.66) + (0.56 \pm 0.07)$.

**Conclusion:** A novel data processing method employing *post facto* field inhomogeneity correction shows significantly improved PNMR thermometry accuracy (± 0.3-0.4 °C). The most accurate temperature *vs.* brain water resonance frequency calibration determined to date (performed on rat brain *in vivo* at 11.74T) is reported and will prove valuable in a wide range of brain temperature studies.

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