Large Dynamic Range Relative B1+ Mapping

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PURPOSE – Ultra-high field MRI suffers from transmit field (B_1^+) inhomogeneity due to electromagnetic wave interference. Parallel Transmission (PTx) offers the ability to mitigate this effect, but requires knowledge of the B_1^+ produced by each transmit element. Two classes of methods have been proposed to measure the B_1^+ field - those designed to measure the B_1^+ magnitude and relative channel phase[1-4], and those designed for measuring relative B_1^+ and relative phase using ratios of low flip angle spoiled gradient echo sequences (LFA-SPGR) for which the image signal intensity is proportional to B_1^+ [5,6]. Studies have investigated the limited accuracy of absolute mapping when the dynamic range is large[7,8]. However these considerations have not been extended to relative mapping, which also suffers from limited measurement accuracy in the presence of large dynamic range due to violating the LFA limit for high B_1^+ areas and encountering the noise floor in low B_1^+ areas. In this work a method for large dynamic range relative B_1^+ mapping is presented. A series of SPGR images are acquired at a number of RF pulse amplitudes. These are retrospectively combined using a maximum likelihood estimator to produce a single image which is proportional to B_1^+ over a wide dynamic range. We demonstrate the proposed method through Monte Carlo simulations and experimentally at 7T with an eight channel torso array coil. **THEORY** – Eqn. 1 describes the signal of an SPGR sequence $S_{i,j}$ (i = transmit channel, j = RF pulse voltage level, $B_{1,i}^+$ = transmit field strength in μT/V, τ converts $B_1^+V_j$ into flip angle, ε = complex noise of standard deviation σ). Figure 1A shows an illustrative plot of eqn. 1 for high and low B_1^+. SPGR linearity is more apparent in the normalised regime $\hat{S}_{i,j}$ (eqn. 2a and Figure 1B), where regions of valid LFA approximation produce constant signal of amplitude $\hat{C}$, which is proportional to M_0, the receive sensitivity and B_1^+. It is the goal of the proposed method to estimate the unsaturated signal $\hat{C}$ for all B_1^+ amplitudes given the measured data. The reconstruction is posed as a Maximum Likelihood Estimation (MLE) problem using the following model. The first k measurements ($\hat{S}_1,\ldots,\hat{S}_k$, $1\le k\le N$) are considered to be drawn from Gaussian distributions with known standard deviations $\hat{\sigma}_j$ (eqn. 2b) and single unknown mean $\hat{C}$, and subsequent samples $\hat{S}_{k+1},\ldots,\hat{S}_N$ are saturated and therefore not consistent. Given this model, the function $L(k,\hat{C})$ (eqn. 3) describes the likelihood that the first k samples are consistent with a single consistent mean $\hat{C}$. $L(k,\hat{C})$ is formed by multiplying a set of probability densities p_j (eqn. 3), which individually give the chance of any sample $\hat{S}_j$ being measured for the assumed $\hat{C}$. The likelihood function is evaluated for all possible k and $\hat{C}$; its maximum is the most likely given the data, and the corresponding value of $\hat{C}$ is used as the best estimate of the signal intensity. This process is repeated for all pixels. **METHODS** – The proposed method was tested both numerically and experimentally. A synthetic dataset was generated using eqn. 1 with the following parameters: $M_0R=1$, τ=0.5ms, TE=4ms, five noise levels such that the corresponding SNR was between 1% and 100% of an SNR measurement from an in-vivo reference scan in a ROI adjacent to a receive element (SNR_{nom}), transmit sensitivities across a large dynamic range from 0.2 nT/V to 200nT/V, the maximum of which was measured on a coil array with large dynamic range, T_2 = 100ms and TR/T1 ratios of 0.01, 0.03, 0.05 and 0.07. The maximum voltage is the maximum output of the 7T Siemens system utilised for this study, and the minimum voltage was based on an SPGR simulation to obtain the voltage level which produced a signal which was linear to 1% accuracy. Two voltage stepping patterns were used – samples at equally spaced voltages, and samples at exponentially spaced voltages such that more were placed at lower voltages. The number of voltages used was varied from 4 to 16 in steps of 2. The simulations were repeated 5 times with different noise seeds. The reconstructed signals were divided by the known correct signal in order to assess their accuracy, in addition to taking the standard deviation across noise repeats. In-vivo experiments were performed on a 7T Siemens system equipped with an 8 channel torso transmit/receive array[9] placed over the thorax in accordance with our institution's ethical practices. The liver was imaged with a 2D SPGR (TR=6ms, TE=2ms, slice thickness=8mm, FOV=500^{2}mm, BW=200Hz/pix), repeated with exponentially-stepped voltages of 3.9V, 14V, 50V and 179V. The scan time was 25s and acquired in a breathhold. Images for all transmit channels were acquired before moving onto the next voltage. **RESULTS** – Figure 2 shows the results of the numerical simulation for TR/T_1 = 0.03. Each graph shows the ratio of the reconstructed signal to the correct value as a function of B_1^+ for different numbers of samples (1 indicates correct solution). At the highest SNR levels both the voltage sampling schemes produce accurate measurements. Decreasing the SNR to <0.1xSNR_{nom}, the linear voltage sampling scheme becomes relatively poor for low B_1^+. Exponential sampling is robust for a wide range of transmit sensitivities and SNR levels, although some downwards bias is present - 4 voltage exponential sampling underestimates the true signal by 3% and 6% at SNRs of 3% and 1% of SNR_{nom} respectively, when averaged across all B_1^+ sensitivities. Figure 3 shows reconstructed in-vivo relative B_1^+ maps for a subset of channels. Using solely low voltage data, the maps have low SNR but are accurate in regions of high B_1^+. Maps created with just the high voltage data suffer from saturation indicated by the suppressed estimates at the edge of the torso but have high SNR in the low B_1^+ regions. The proposed method provides maps which are consistent with both extremes and are sensible in the intermediate regions. **DISCUSSION & CONCLUSIONS** – Possible extensions to this work include the ability to extend the $L(k,\hat{C})$ to include further information, such as the increase in saturation past the linear regime. We have shown the feasibility of accurate large dynamic range relative B_1^+ mapping. The use of short TRs allowed 8 channels to be mapped in a breathhold.

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$$[1]\quad S_{i,j} = \frac{M_0R(1-e^{-TR/T_1})\sin(\gamma\tau B_{1,i}^+V_j)}{1-e^{-TR/T_1}\cos(\gamma\tau B_{1,i}^+V_j)} + \epsilon(\sigma)$$

$$[2a]\quad \hat{S}_{i,j} = S_{i,j}/V_j \qquad [2b]\quad \hat{\sigma}_j = \sigma/V_j$$

$$[3]\quad L(k,\hat{C}) = \prod_{j=1}^{k} p_j, \quad \text{where} \quad p_j = \frac{1}{\hat{\sigma}_j\sqrt{2\pi}}e^{-\frac{(\hat{S}_j-\hat{C})^2}{2\hat{\sigma}_j^2}}$$

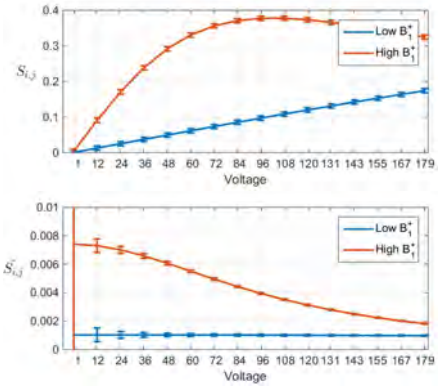

Fig. 1 – SPGR curve pre and post division

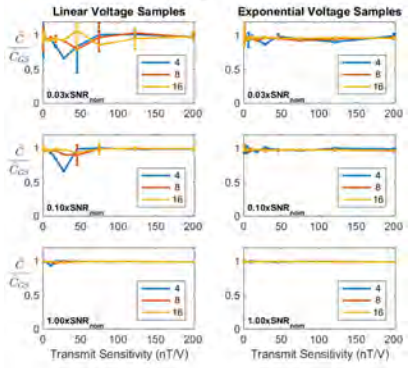

Fig. 2 – Simulation results

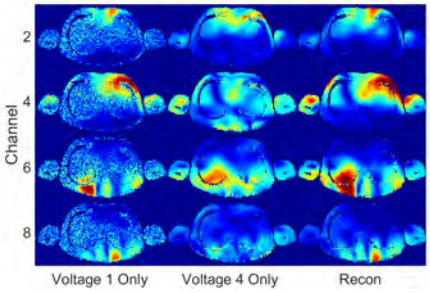

Fig. 3 – In-vivo relative B_1^+ Maps