Isotropic Mapping of $T_1$, $T_2$, and $M_0$ with MP-DESS and Phase-Graph Data Fitting

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Introduction: Quantitative MRI (qMRI) of the human brain provides important insights into certain pathologies [1]. Isotropic, high resolution is best achieved with a 3D sequence – i.e. a 2D phase encoded (PE) acquisition – using short TR (<$T_2$). This leads to biased parameter estimates in qMRI approaches where perfect spoiling is assumed [2], for instance Look-Locker approaches. Thus, it is important to incorporate transverse relaxation into the signal equation, as has been carried out in transient balanced SSFP [3-4], which is however prone to banding artefacts induced by B$_0$-inhomogeneities. Here, a double echo steady state sequence [5] with magnetization preparation, MP-DESS, is utilized to overcome these limitations. An accurate signal equation for least squares data fitting is provided by the extended phase graph [6]. Along the MP-recovery the DESS images, $S_+$ and $S_-$, are individually reconstructed. The $S_+$ state (the “FID”) provides a higher SNR whereas the $S_-$ state (the “Echo”) has a more pronounced $T_2$ weighting. Together they provide high sensitivity for the parameters under investigation, i.e. $M_0$, $T_1$, and $T_2$.

Methods: In a standard 3D-DESS sequence with rectangular pulses of flip-angle $\alpha$, every Nth pulse is replaced by a rectangular 180° pulse. The recovery echo train of length N is divided in L segments of size M which encode the same k-space, giving L/N=M different images for $S_+$ and $S_-$, respectively (Fig.1). The outer MP loop has to be performed $N_1\times N_2 \times N_3$ times, where $\{N_1, N_2, N_3\}$ denote the PE matrix size. The signal is modelled with the extended phase graph. Since performing these calculations on a voxel-by-voxel basis for data fitting is far too slow, a parallelised computation matching the sequence parameters is pre-calculated on a suitable grid $\{T_1, T_2, W_{xy}\}$, where $W_{xy}$ denotes a spatial $B_1$ weighting factor, common for the $\alpha$-pulse and the 180° pulse. This results in a “signal database”, ($S_i^+, S_i^-, i=1, \ldots, L$), showing a smooth dependence on the relaxation times. $M_0$ is a common scaling factor of the signal levels. The signal database is well-suited for rapid tri-linear interpolation in least-squares cost function minimisation: $cry = \sum_{i=1}^{L} \left( \frac{S_i^+ - \hat{S}_i^+}{\hat{S}_i^+} \right)^2 \left( \frac{S_i^- - \hat{S}_i^-}{\hat{S}_i^-} \right)^2$. Consequently, the fitting of $10^3$ voxels needs less than five minutes on an up-to-date desktop PC. Data were acquired on a Siemens TIM-Trio scanner with a 12-channel head coil array (Siemens, Erlangen). $W_{xy}$ was mapped with the 3D AFI sequence [7] (TR1/TR2=5). Receiver sensitivity was corrected by means of a body-coil FLASH image. MP-DESS echo trains were acquired for an agarose phantom and the fitting result compared to $T_1$, $T_2$, and $M_0$ maps were calculated. The MP-DESS sequence parameters were as follows: matrix size=160×160×120, flip-angle $\alpha = 10°$, resolution = 1.4 mm (isotropic), TR/TE$_0$/TE$_{xy} = 10/3/7$ ms, bandwidth = 270 Hz/Pixel, N/L = 360/9, parallel imaging acceleration = 2, and the acquisition time totalled 15 minutes.

Results: Sample slices of the MP-DESS signal database are depicted in Fig. 2a, showing a smooth signal variation with relaxation times. From these the cost function is calculated, shown in Fig. 2b for target parameters $T_1/T_2=1000/100$ ms. It displays a pronounced global minimum enabling robust parameter estimation in the presence of noise. Fig. 3 compares the echo train measurement and the computed signal amplitudes, showing a nearly perfect match between phantom data and the phase graph signal description. The fitted relaxation time-estimates, $T_1/T_2=1683/83$ ms, agree with the gold standard spectroscopic evaluation to less than 3% and 8% for $T_1$ and $T_2$, respectively. MP-DESS in vivo images and parameter mapping results are plotted in Fig. 4. Estimation of cortical relaxation times and the relative spin density agree well with the literature [8].

Conclusion: This work presents a novel method for accurate, 3D, high-resolution parameter mapping with time efficient data acquisition, as the MP-DESS sequence and the corresponding phase-graph signal model do not rely on any inter-sequence recovery dead-times. Although the echo train resembles an inversion recovery, the sequence is best understood as generating N different steady states through inversion/refocusing pulses replacing every Nth $\alpha$-pulse. MP-DESS acquires $B_0$-insensitive and artefact-free images, as opposed to fully balanced SSFP. Utilising non-selective RF pulses increases the mapping accuracy, as they allow for fast and robust mapping of the $B_0$ with AFI [7]. The $S_+$ and $S_-$ images provide a robust cost function minimisation which is best achieved at low flip-angle $\alpha$. The latter reduces MT effects and supports high field applicability.