SNR-Optimized, Fast, and High-Resolution Mapping of Whole Brain Tissue Water Content

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Introduction

Accurate mapping of tissue water content, M0, with high spatial resolution and short experimental times is technically challenging. One efficient method for obtaining simultaneous M0 and T1-maps is based on acquiring two spoiled gradient recalled echo (SPGR) images in steady states with variable flip angles. Linear parameterization is used to simultaneously estimate the T1 and M0 values (1,2). The two optimal flip angles for best T1-maps (*i.e.*, maximum SNR) were previously found both numerically (1) and analytically (2). Here, we demonstrate that these flip angles, however, are not optimal for best M0-mapping. Therefore, we analytically derive the optimal flip angles for SNR-optimized M0-maps and verify the result in eight healthy subjects. Accurate M0-maps with 1 mm isotropic and full brain coverage were achieved in a clinically acceptable time (6:30 min).

Theory: The steady state SPGR signal is given by: $S = M_0 \cdot \frac{1-e^{-TR/T_1}}{1-\cos(\alpha)e^{-TR/T_1}} \cdot \sin(\alpha) \cdot e^{-TE/T_2^*}$ [1], where M0 is the equilibrium magnetization directly proportional to the voxel water content. If only two acquisitions with flip angles α_1 and α_2 (*i.e.*, S_1 and S_2) are performed, $M_0 E^*$ can be calculated from linearization of Eq [1] by: $M_0 E^* = \frac{AS_2 S_1}{BS_2 - CS_1}$ where: $A = \sin(\alpha_2)\tan(\alpha_1) - \sin(\alpha_1)\tan(\alpha_2)$, $B = \tan(\alpha_1)\sin(\alpha_1)(\sin(\alpha_2) - \tan(\alpha_2))$, $C = \tan(\alpha_2)\sin(\alpha_2)(\sin(\alpha_1) - \tan(\alpha_1))$, and $E^* = \exp(-TE/T_2^*)$. Provided that the two measurements S_1 and S_2 are performed with the same bandwidth and receiver gain, the noise level σ_s is the same in both images. The noise in the M_0-map is then given by: $\sigma_{M_0} = \sqrt{\left(\frac{\partial M_0}{\partial S_1}\right)^2 + \left(\frac{\partial M_0}{\partial S_2}\right)^2}\,\sigma_s$

Calculating the partial derivatives and replacing them into this equation yields:

$\sigma_{M_0} = A\frac{\sqrt{B^2 S_2^2 + C^2 S_1^2}}{(BS_2 - CS_1)^2}\sigma_s$ [2]. To maximize the SNR in the M0-map, the pair of flip angles (α_1, α_2) minimizing Eq. [2] can be found numerically (Figure 1).

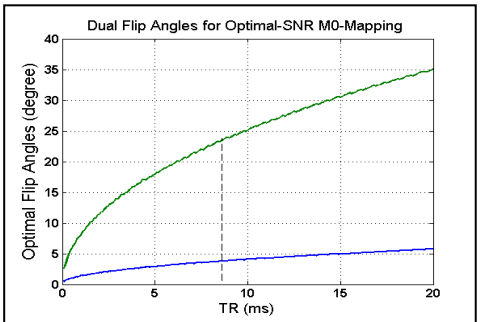

Fig 1: Optimal flip angles in terms of TR for maximum-SNR M0 mapping obtained by numerical solution of Eq. [2]. T1 = 1000 ms was assumed.

Methods: The approach presented above gives rise to a low flip angle (<6˚) for relatively low TRs (<20 ms) for which the SPGR signal can be approximated with: $S \propto M_0 \cdot \sin(B_1\alpha) \cdot e^{-TE/T_2^*} \propto M_0 B_1 \alpha$, where B1, the actual-to-nominal flip angle ratio, describes the flip angle inhomogeneity (3,4). Because B1 is a spatially smooth function and e^{-TE/T_2^*} is pixel independent, the B1 map can be approximated by heavily smoothing the low-flip angle SPGR signal (3,4); and then used for more accurate M0 estimation. Eight healthy subjects were scanned at 3.0 T (Trio/TIM; Siemens) using an 8-ch phased-array head coil. Four variable flip angle SPGR scans with the following parameters were used: TR/TE=8.4/3.76 ms, α1=4°, α2=15°, α3=23°, α4=27°, matrix=256×256, BW=210 Hz/Px, FOV=256×256 mm^2, 160 slices, 1 mm slice thickness, iPAT factor = 2, and 3:14 min per each scan. Three pairs of SPGR scans with flip angles **(a)** α1=4°, α2=15° (optimal flip angles for T1 mapping, *c.f.* Refs (1,2)) **(b)** α1=4°, α2=23° (optimal flip angles for M0 mapping, see Figure 1) and **(c)** α1=4°, α2=27° were used for map reconstructions. These were compared to maps reconstructed using all four scans by linear least square estimation (reference map; Ref M0). T1 in CSF was limited to 3000 ms and M0 values were normalized to CSF in the ventricles and assuming 98% water content. The M0-maps were spatially transformed to a common spatial reference (MNI) and mean values in atlas-defined brain regions (*i.e.*, frontal, temporal, parietal, occipital lobes) calculated for each subject, using the four different flip angles combinations.

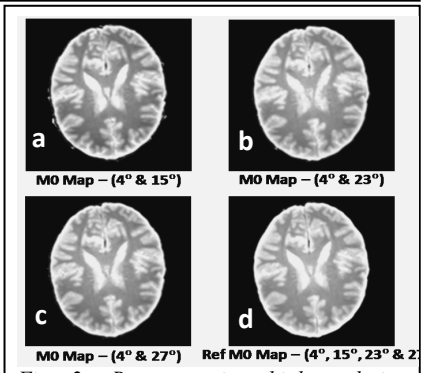

Fig 2: Representative high-resolution images of the B1-corrected M0 maps, obtained with a) (4°,15°); b) (4°,23°); c) (4°,27°); and d) (4°,15°,23°,27°). All images displayed at the same scale.

Results and Discussion: Figure 2 shows one slice of the estimated M0 maps from a healthy subject using various flip angle combinations. The pair (4°, 23°) M0-map (Fig 2b) illustrates minimal difference to the reference M0-maps, supporting the analytical solution of Eq. [2]. Mean M0 values for each of the atlas-defined brain regions and tissue type from the 8 healthy subjects are given in Table 1. These results also confirm that the (4°, 23°)-pair estimated the water content most accurately (in comparison with the values found in literature (5) and the Ref M0 values). The other flip angle combinations underestimated the tissue M0 values.

Further acquisitions with external references are usually required to obtain the absolute brain tissue water content. Several factors, including B1, particularly at higher filed strengths, and low SNR may negatively affect the accuracy of these methods and produce systematic errors in M0 estimation (6). Absolute values can still be achieved by applying suitable corrections (5). However, the concomitant increase in scan time renders these techniques intractable in a clinical environment. High spatial resolution with full brain coverage M0 mapping was achieved in this study by an optimized B1-adjusted SPGR variable angle method that is suitable for neurological clinical research. Water content maps together with other quantitative maps provide larger range of contrast than conventional images, which may improve the accuracy of the segmentation.

Table 1: Mean M0 values in each brain region and GM/WM tissue from 8 healthy subjects.

Brain region / Brain tissue	Frontal		Temporal		Parietal		Occipital	
	L	R	L	R	L	R	L	R
Gray matter								
M0 – Ref	0.722	0.720	0.789	0.768	0.710	0.690	0.795	0.781
M0 – (4°, 23°)	0.707	0.691	0.766	0.732	0.676	0.677	0.782	0.765
M0 – (4°, 15°)	0.605	0.591	0.669	0.655	0.593	0.601	0.696	0.671
White matter								
M0 – Ref	0.597	0.594	0.659	0.623	0.642	0.6142	0.616	0.585
M0 – (4°, 23°)	0.569	0.566	0.637	0.603	0.612	0.585	0.606	0.557
M0 – (4°, 15°)	0.488	0.481	0.551	0.512	0.521	0.494	0.516	0.468

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References: (1) Deoni SCL *et al*, MRM 2003; 49:515. (2) Preibisch C *et al*, MRM 2009; 62:240. (3) Sabati M *et al*, ISMRM 2010; 18:2317. (4) Helms G *et al*, MRM 2008; 59:667. (5) Neeb H *et al*, Neuroimage 2008; 42:1094. (6) Fleysher R *et al*, MRI 2008; 26: 781.