MIRACLE: Motion-Insensitive RApid Configuration reLaxomEtry

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Target Audience: physicists and clinicians interested in new relaxometry methods

Purpose: Acquisition of low order configuration images with unbalanced steady state free precession (SSFP), e.g. with triple-echo steady state (TESS) [1,2], allows rapid relaxometry with an exceptional insensitivity to transmit field (B1) variations for T_2 but suffers from a strong sensitivity to motion. To this end, we propose to bypass the motion-sensitive unbalanced SSFP scheme with a series of balanced SSFP acquisitions with different radio-frequency (RF) phase increments to yield a base for Motion Insensitive RApid Configuration reLaxomEtry, termed MIRACLE.

Methods: We make use of a seminal concept for motion-insensitive SSFP imaging, as introduced by Zur et al. in 1990 [3], namely that SSFP configurations or modes can be derived from a *N*-point discrete Fourier transform of *N* balanced SSFP (bSSFP) datasets with different equidistant RF phase increments $\phi_j = 360 \times (j-1)/N$ [°] for j = 1…N. After derivation of the lowest order modes, e.g. F_{-1}, F_0, and F_1, estimation of both T_1 and T_2 is realized with an iterative golden section search algorithm, as described previously [1]. MIRACLE acquisitions and patient-specific B1 data were collected on a 3T whole body system (Siemens MAGNETOM Prisma) with a standard 20-channel headcoil. Phantom experiments (0.125 mM [$MnCl_2$], T_1 / T_2 of 880 / 70 ms) were performed with a series of N = 8 cycled three-dimensional (3D) bSSFP scans with a TR / TE of 5.76 / 2.88 ms, α = 15°, 1x1x3 mm^3 resolution, $\phi_j = 0$, 45, 90, …, 315 [°], yielding an overall scan time of approx. 8 min. In vivo 3D MIRACLE imaging of a slab (30 slices) located inside the brain was performed using a *N* = 12 bSSFP cycling scheme (ϕ_j = 0, 30, 60, …, 330°) with a TR / TE of 5.76 / 2.88 ms, α = 15°, resolution 1x1x2 mm^3 and an overall scan time of approx. 5 min. Generally, MIRACLE T_1 and T_2 mapping was compared to reference single-echo single-slice spin echo (SE) relaxometry.

Results: Simulations for a *N* = 8 discrete Fourier transform of a series of bSSFP acquisitions show that the retrieved amplitudes for the lowest order modes, i.e., F_1, F_0 and F_{-1} deviate by less than 0.8% from their original values, but significant aliasing occurs for modes F_n with $|n| > 2$ (Fig. 1). As a consequence, derived T_1 / T_2 of 886.4 / 69.3 ms are in excellent agreement with the nominal ones (880 / 70 ms). This is further confirmed by phantom results (see Fig. 2), revealing - after B1 correction - an excellent agreement for the observed MIRACLE T_1 / T_2 (832 / 70 ms) with TESS relaxometry (840 / 70 ms), and very good agreement with SE-based relaxometry (880 / 70 ms). Generally, as already observed with TESS, MIRACLE T_2 relaxometry shows an intriguing B1 insensitivity, while T_1 shows the expected B1 dependency.

Brain relaxometry was realized with a N = 12, rather than a N = 8, bSSFP acquisition scheme, yielding improved stability. For deep white matter, a typical T_2 of 50 ± 5 ms is found, whereas a T_2 of 58 ± 7 ms is observed for gray matter (caudate nucleus); see Fig. 3. These findings are in excellent agreement with recent observations using TESS [2]. After B1 correction, a corresponding T_1 of 532 ± 52 ms and 951 ± 110 ms is observed for white and gray matter respectively. For cortical gray matter a T_1 / T_2 of 1140 / 80 ms is found.

Discussion & Conclusion: Although excellent agreement between MIRACLE and reference SE relaxometry data is observed, it appears that – in contrast to the observed T_2 values – B1-corrected brain T_1 values are systematically underestimated for both gray and white matter. A possible explanation for this intriguing phenomenon could be the presence of an asymmetric distribution of frequencies within the voxel leading to asymmetries in the bSSFP profile, as recently discovered by Miller [4]. This explanation is further supported by the observation that the asymmetry is larger for white as compared to gray matter; this being in line with the increased deviation from the nominal T_1 of white matter (500 ms vs. 900 ms) compared to gray matter (1000 ms vs. 1200 ms). If the origin of this effect can be found in the asymmetric bSSFP frequency profile, this would point towards a diametral T_1 microstructure in these tissues, but clearly further research is required to understand and identify the underlying mechanisms.

In summary, MIRACLE allows rapid 3D motion-insensitive estimation of both T_1 and T_2 from a series of bSSFP datasets. Similar to TESS, T_2 quantification with MIRACLE is robust and insensitive to B1 field inhomogeneities. Estimation of T_1, however, appears to be systematically underestimated for tissues, possibly resulting from a recently discovered asymmetry in the bSSFP frequency profile.

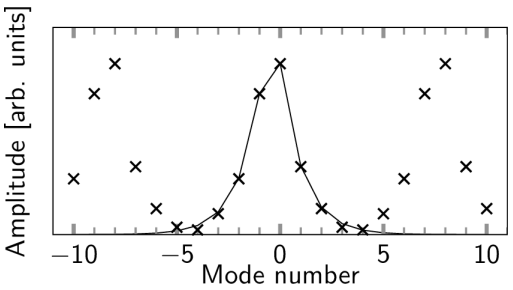

Fig. 1 Simulated mode amplitudes for a given T_1 / T_2 of 880 / 70 ms from a fully sampled bSSFP profile (solid line) and a discrete series of N = 8 bSSFP signals (cross).

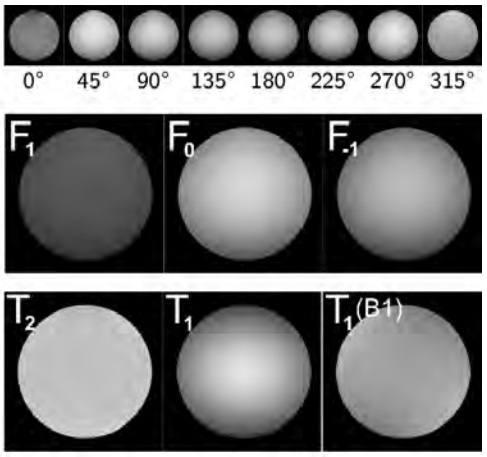

Fig. 2 MIRACLE phantom evaluation using N = 8 bSSFP cycles. (**a**) Individual bSSFP images, (**b**) reconstructed mode amplitudes, (**c**) estimated T_1 / T_2 maps.

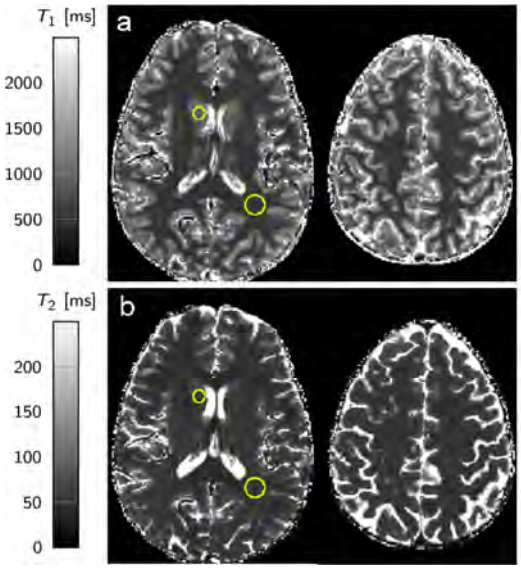

Fig. 3 Illustrative T_1 (**a**) and T_2 maps (**b**) from a 3D MIRACLE data acquisition (30 slices) after B1 correction showing two different axial slices. Overall scan time approx. 5 min.

References: [1] R. Heule et al., MRM 71 (2014) 230-237, [2] R. Heule et al., NMR Biomed 27 (2014) 1037-1045 [3] Y. Zur et al. MRM 16 (1990) 444-459, [4] K. Miller, MRM 63 (2010) 385-395