Comparison of T1-Weighted 3D High-Resolution Anatomical Sequences for the Brain at 3 Tesla: FLASH, MP-RAGE and MDEFT

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Introduction: The outcome of automated quantitative morphometric population studies relies greatly on the quality of the cerebral anatomical images. For these applications, it is crucial that the images be uniform and have high spatial resolution, SNR (signal-to-noise ratio) and CNR (contrast-to-noise ratio) between brain tissues. This study evaluates the performance of three different T_1-weighted pulse sequences at 3T (Tesla) in terms of SNR and CNR efficiency, as well as signal intensity NU (non-uniformity): FLASH (fast low angle shot), MP-RAGE (magnetization prepared rapid acquisition by gradient echo), and MDEFT (modified driven equilibrium Fourier transform). In both MP-RAGE and MDEFT, the 3D-FLASH readout is preceded by a magnetization preparation period to modify the contrast characteristics in a time-compact sequence design. The MP-RAGE preparation consists of an inversion pulse followed by a delay TI before the readout. The MDEFT preparation consists of two pulses: first a saturation pulse immediately followed by spoiler gradients to remove transverse magnetization then, after a time delay $\tau 1$, an inversion pulse is applied followed by an additional delay $\tau 2$. The total preparation time is TI= $\tau 1+\tau 2$. The inner centric 3D phase encoding loop of the readout in MDEFT is divided into 2 segments. Our objective was to determine the optimal 3T sequence for automated image analysis, and to identify further challenges that need to be addressed.

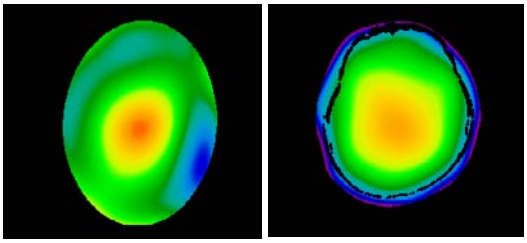

Figure 1: B_1 field map of elliptical phantom (left) and human brain (right). Scale [0.5, 1.2].

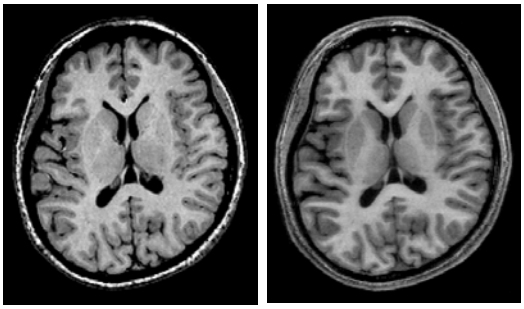

Figure 2: FLASH (left) and MDEFT rect.150 (right) axial image of the human brain.

Methods: All data was acquired on a Siemens Trio 3T imaging system with a circularly polarized head coil. The FLASH sequence chosen corresponds to the Siemens standard 3D high-resolution brain imaging protocol on the scanner, with parameters α/TE/TR set to 25°/7.38ms/23ms. The MP-RAGE sequence was adapted from the ADNI (Alzheimer's disease neuroimaging initiative) research protocol [1], with parameters TI/α/TE/TR set to 900ms/9°/2.96ms/2300ms. The MDEFT sequence is based on the implementation of Deichmann *et al.* [2], with parameters TI/$\tau 1$/α/TE/TR set to 680ms/319.6ms/22°/3.14ms/1608.4ms. Its magnetization preparation was modified to include a BASSI (bandwidth modulated adiabatic selective saturation and inversion) saturation pulse [3]. Also, multiple inversion pulses were tested in order to find the best image uniformity: an HS (hyperbolic secant) pulse, and a rectangular pulse of 150°. All three sequences have matching fields-of-view of 176x224x256 mm^3 and 1mm isotropic resolution, with scan times of 15:07, 8:37 and 12:08 for FLASH, MP-RAGE and MDEFT respectively. A uniform elliptical phantom with similar dimensions, electrical properties and relaxation properties to the human head was designed to study B_1 excitation field, and resulting image, NU. Two additional cylindrical phantoms mimicking WM (white matter) and GM (grey matter) were designed to study the SNR and CNR characteristics. The T_1 relaxation times of the WM and GM phantoms, estimated using DESPOT1 [4], were 865.8±15.6 ms and 1337.6±29.9 ms respectively. The phantom results were compared to the results from two healthy young volunteers.

Table 1: Uniformity study results: phantom and human subjects.

Pulse sequence	Phantom		Subject 1	Subject 2
	σ_{norm}	$\sigma_{NUfield}$	$\sigma_{NUfield}$	$\sigma_{NUfield}$
FLASH	0.1288	0.1152	0.0380	0.0428
MP-RAGE	0.2117	0.1448	0.0721	0.0758
MDEFT HS	0.3006	0.1519	0.1121	0.0926
MDEFT rect.150°	0.1362	0.1210	0.1375	0.0891

Table 2: SNR and CNR results of the brain tissue mimicking

Pulse sequence	CNR/√Time	SNR_{WM}/√Time	SNR_{GM}/√Time
FLASH	0.43	3.52	3.10
MP-RAGE	0.24	1.32	1.08
MDEFT HS	0.38	1.62	1.25
MDEFT rect.150°	0.47	1.84	1.37

Table 3: SNR and CNR results of the human subjects.

Pulse sequence	CNR/√Time	SNR_{CC}/√Time	SNR_{CN}/√Time
FLASH	0.24	1.89	1.66
MP-RAGE	0.24	0.88	0.64
MDEFT HS	0.60	1.72	1.12
MDEFT rect.150°	0.80	2.24	1.45

Results: The elliptical phantom B_1 field map had a similar range and distribution to that of a human brain, as presented in Figure 1. In Table 1, the phantom NU results are displayed in terms of the standard deviation σ_{norm} of the images normalized by the mean signal intensity. The elliptical phantom and cerebral images were corrected using N3 (nonparametric non-uniform intensity normalization) [5]. The standard deviations $\sigma_{NUfield}$ of the NU correction fields applied are also listed in Table 1. The SNR and CNR results, divided by the square root of the scan time, for the WM and GM mimicking phantoms are listed in Table 2. The SNR values are scaled by the relative PD (proton density) factor for WM and GM, 0.65 and 0.75 respectively. The SNR and CNR results for the two human subjects are listed in Table 3. The regions of interest chosen are the genu of the CC (corpus callosum) and the head of the CN (caudate nucleus).

Discussion: The elliptical phantom NU results demonstrate that FLASH was the most insensitive to B_1 field inhomogeneity, closely followed by MDEFT with a rectangular 150° pulse. The B_1-sensitive rectangular pulse of the MDEFT sequence partially compensates for the excitation pulse, as previously demonstrated by Thomas *et al.* [6]. Although N3 did improve the uniformity of all images, the estimated variation does not precisely match the true NU in the image and may reduce naturally occurring biological variations in tissue. In addition to image uniformity, the MDEFT sequence with a rectangular 150 pulse out-performs the sequence with an HS pulse with respect to SNR and CNR efficiency. MDEFT-rect.150 has the highest CNR efficiency for both the phantom and human subjects results, which makes this sequence best suited for applications that require WM-GM tissue segmentation. FLASH shows a significantly higher SNR efficiency in the phantom images than for MDEFT. However, the reverse is observed for the genu of the corpus callosum. This is mainly caused by the differences in sensitivity to B_1, particularly due to the central position of the chosen ROI in the brain genu, but may also be caused by differences in T_1 and proton density with respect to the phantoms. MP-RAGE, with the shortest scan time of 8:37, is out-performed by FLASH and MDEFT in terms of uniformity, as well as SNR and CNR efficiency. These results suggest that at 3 Tesla it is preferable to implement MDEFT with parallel-imaging or partial k-space sampling methods to reduce the scan-time than to use MP-RAGE. MDEFT has a disadvantage with respect to FLASH that is not explicitly included in this study: blurring due to T_1 relaxation during the long readout. This will cause the point spread function to broaden, leading to blurring in the 3D phase-encode direction of the image, which can degrade segmentation results at tissue boundaries. The blurring effect may also slightly increase the image SNR.

[1] www.loni.ucla.edu/ADNI/Research/Cores; [2] Deichmann *et al.,* NeuroImage 21:757-67 (2004); [3] Warnking & Pike, Magn.Reson.Med. 52:1190-9 (2004); [4] Deoni *et al.,* Magn.Reson.Med. 53:237-41 (2005); [5] Sled *et al.,* IEEE Trans.Med.Imag. 17:87-97 (1998); [6] Thomas *et al,.* Magn.Reson.Med. 53:1452-8 (2005).