A simple method to denoise MP2RAGE

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Introduction: MP2RAGE [1,2] simultaneously acquires a 3D T1w MPRAGE (GRE_{TI1}) and a 3D GE-PD (GRE_{TI2}) image to correct for: proton density; T2* contrast; and, B1 inhomogeneities at high fields (≥3T). The "uniform" or self-bias field corrected image is obtained by taking either the simple {1} or complex {2} ratio of these two images at the expense of amplifying the noise, figure 1. The high background noise and the increased noise level in the meninges are problematic for registration and automatic segmentation algorithms [1,3]. A common approach to deal with this noise has been to add an additional pre-processing step, of either applying a binary mask [1] or multiplication followed by a global scaling correction [3] with the GRE_{TI1} image, to remove the background noise. Though effective, these approaches risk thresholding out data from inside the brain or in case of the later reintroduce the proton density, T2* contrast and B1 inhomogeneities biases back into the image. In addition, poor inversion in the cerebellum and neck results in a low SNR in the GRE_{TI1} and GRE_{TI2} images and consequently regions of bright signal intensity in the ratio image, figure 1, which can not be removed with a simple threshold and would still interfere with registration. In this work, we propose simple modifications to the ratio calculations that remove the numerical instability, suppress the noise and recover contrast in regions of low SNR.

Theory: The background noise is a result of the numerical instability when dividing voxels with a very low SNR. If the biases are removed using the simple ratio, the value diverges when the signal of the denominator is low or noise [1]. The complex ratio presented in [2] has the advantageous property that it limits the values of the image between -0.5 and 0.5 but remains numerically unstable when both modules are small. This, added to the fact that the phase points in any arbitrary direction when the SNR is low [4], means that the noise takes on a "salt and pepper" characteristic. It spreads across the range -0.5 and 0.5. By introducing the variable γ into each ratio, equations 1 and 2, the signal can be forced towards either 0 or -0.5 when the voxel SNR is low or noise. The value of γ must be carefully chosen to ensure that it dominates noise without significantly impacting voxels with signal, where the self bias correcting properties of the ratio calculation are desired.

Methods & Materials: Whole brain MP2RAGE acquisitions from 8 subjects were acquired on a Magnetom 7T whole-body scanner (Siemens Healthcare Sector, Germany) with a single-channel transmit and 32 channel receive volume coil (Nova Medical Inc, MA, USA). Each subject was scanned twice during a separate scan session. Typical image parameters were TR/TE/ 6s/2.89ms TI_1/TI_2 0.8s/2.7s Matrix 256x240x176, voxel 1.0x1.0x1.2mm. The ratio images were retrospectively reconstructed using the GRE_{TI1} and the GRE_{TI2} magnitude and phase images with the complex ratio formulation, equation 2. To remove noise whilst minimizing the bias introduced back into the images, γ was tuned by maximizing the image negentropy [4] over positive real numbers subject to a linear penalty to favor small offset values. Numerical optimization was carried out using Brent's method and took ~1min on a standard single processor PC. The images were subsequently linearly transformed to scale between 0 and 4095.

$$S = \frac{|GRE_{TI1}|}{|GRE_{TI2}| + \gamma} \quad \{1\}$$

$$S = \mathrm{Re}\left(\frac{GRE^{*}_{TI1}GRE_{TI2} - \gamma}{|GRE_{TI1}|^{2} + |GRE_{TI2}|^{2} + 2\gamma}\right) \quad \{2\}$$

Results: The introduction of γ suppresses the salt and pepper noise outside and inside the skull, figure 1. In regions of low signal intensity, the contrast is recovered (neck) and structures become better delineated (cerebellum). The bias that is introduced in the brain is small (μ=-5.8%±5.5%) and is slowly varying across the brain, which is easy to correct in a later image segmentation step [6]. Table 2 shows that the relative differences between standard and optimized calculations are consistent across repeat scans.

Discussion: Our proposed modification to the MP2RAGE calculations, are a tradeoff between the self-bias correcting properties of the ratio and numerical stability. The small bias introduced is manageable and visually improves the images so that they appear like a customary T1w image. The recovery of contrast in regions of low SNR and better delineation of structures with the optimized calculation will aid morphometry packages, in particular the segmentation of the total intracranial volume which is a key step in brain tissue classification. Different penalty factors could be applied depending on the user's preference for noise suppression or maintaining the self bias correcting properties of the MP2RAGE calculation. **In Conclusion,** we have provided a simple modification and optimization procedure to suppress the noise that inherently occurs when taking the ratio of images, which when applied to MP2RAGE scans returns familiar T1w images.

References: **[1]** Van de Moortele P. 46(2009)432 Neuroimage **[2]** Marques J. 49(2010)1271 Neuroimage **[3]** Fujimoto K, Proc 20th ISMRM #130 **[4]** Hákon G. 34(1995)910 MRM **[5]** Hyvärinen A. 13(2000)411 Neural networks **[6]** Van Leemput K. 18(1999)885 IEEE TMI

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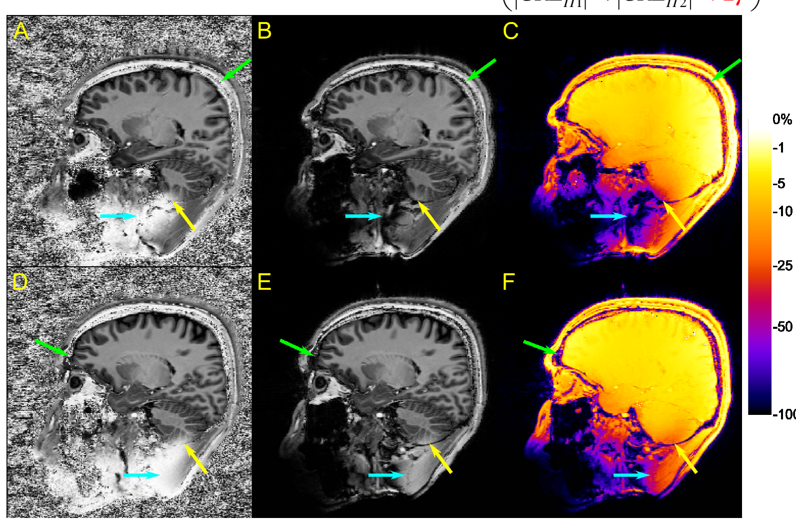

Figure 1 Two different sagittal slices acquired in the first (A-C) and repeat scan session (D-F) of the same subject with the standard (A,D) optimized (B,E) and the relative difference ($^{x-y}/_{x}$) between the optimized and standard ratio calculations. Arrows indicate regions where: the noise has been suppressed inside the brain (green); contrast has been recovered (blue); and, structures are now better delineated (yellow) in the optimized calculation.

	Repeat 1		Repeat 2		Rel Diff (Std -Optim)		Rel. Diff (Repeat 1 - Repeat 2)	
	Std	Optim	Std	Optim	R1	R2	Std	Optim
Corpus Callosum genu	2485 ± 113	2382 ± 110	2507 ± 108	2395 ± 106	-4.3% ± 4.6%	-4.6% ± 4.4%	-0.9% ± 4.5%	-0.6% ± 4.6%
Corpus Callosum Splenium	2566 ± 95	2448 ± 92	2566 ± 99	2439 ± 94	-4.7% ± 3.7%	-5.1% ± 3.9%	0.0% ± 3.8%	0.4% ± 3.8%
Caudaute Head	1470 ± 115	1398 ± 110	1454 ± 107	1375 ± 102	-5.1% ± 7.9%	-5.6% ± 7.4%	1.1% ± 7.6%	1.7% ± 7.7%
Caudate Body	1586 ± 98	1507 ± 92	1586 ± 114	1498 ± 108	-5.1% ± 6.1%	-5.8% ± 7.4%	0.1% ± 6.8%	0.8% ± 6.8%
Hippocampus	1002 ± 204	910 ± 190	980 ± 198	884 ± 186	-9.7% ± 21.0%	-10.5% ± 20.4%	1.8% ± 20.6%	2.6% ± 21.3%
Dentate nucleus	2054 ± 97	1855 ± 95	2044 ± 105	1826 ± 106	-10.3% ± 4.9%	-11.4% ± 5.5%	0.5% ± 5.0%	1.6% ± 5.5%
Putamen	1758 ± 124	1667 ± 116	1762 ± 131	1661 ± 124	-5.3% ± 7.1%	-5.9% ± 7.6%	-0.2% ± 7.4%	0.4% ± 7.3%
Amygdala	1181 ± 230	1078 ± 214	1150 ± 198	1038 ± 182	-9.2% ± 19.7%	-10.4% ± 17.8%	2.5% ± 18.6%	3.7% ± 19.0%

Table 1 Signal values for the standard and optimized MP2RAGE calculation of various structures and the relative difference ($\mathrm{Rel.Dif} = {}^{x-y}/_{x+y}$).