Improving TOF angiography contrast homogeneity with B1+ shimming at 7 Tesla: benefits and challenges

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INTRODUCTION. In Time-of-flight (TOF) angiography a contrast is generated between static tissues, partially saturated due to a high flip angle (α=20-30º) with short TR<<T_1, and vessels, with strong signal from fresh inflowing blood in the slab. Benefiting from a higher intrinsic Signal to Noise Ratio and from longer T_1 relaxation times compared to lower field strengths, TOF studies at 7T provide good vessel to background contrast [1-3]. However, a significant drawback observed at 7T is the spatially inhomogeneous magnitude of transmit B1 (B1+), resulting in non-uniform TOF contrast. The aim of this work was to investigate the potential and challenges of using B1+ phase shimming to improve the uniformity of TOF contrast in the brain at 7T.

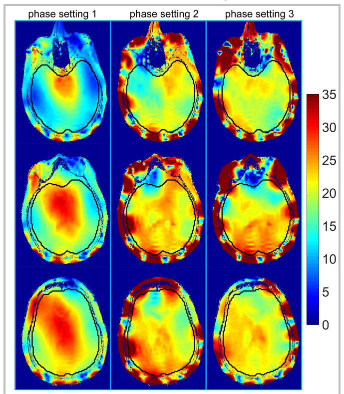

Fig.1: *|B1+| maps in degree corresponding to the TOF angiograms in Fig.2 for the 3 different phase settings. The flip angle was scaled in #2 and #3 according to the RF pulse voltage in Table 1.*

METHODS. Healthy volunteers who signed an IBR approved consent form were imaged at 7T (Siemens), using an elliptical 16-channel transceiver coil [4] powered by 16 1kW amplifiers. A TOF sequence with following parameters was used: TR/TE=33ms/3ms, 3 slabs at 24mm, flip angle α=24° (nominal), overlap: 25%, FOV=220x172x60mm^3, resolution=(0.5mm)^3, Grappa=3 (PE), partial fourier=6/8 (SL). A VERSE algorithm similar to [5,6] was used for excitation RF pulse, that limited the RF magnitude to 50% of the initial pulse peak magnitude. No additional RF pulses (such as presaturation or MT) were used. Fast multi channel B1+ mapping was performed as described in [7] to calibrate the 16 complex B1+ maps, based on 2D GRE series (nominal α =8°) with 3 slices placed in the center of each TOF slab and on a 3D Actual Flip Angle (AFI) acquisition (nominal α=60°) [8]. For B1+ phase optimization, a large ROI was defined on each slice (see Fig 1). TOF angiograms were acquired with 3 different B1+ phase solutions: #1) incremental phases (step = 22.5º) between the 16 channels ; #2) a single B1+ phase shim set calculated over the 3 slabs; #3) one B1+ phase shim solution calculated for each slab. For B1+ shim solutions, the transmit phase of each channel was obtained with non linear optimization tools in Matlab (The Mathworks) by minimizing within the defined ROI(s) an Inhomogeneity Coefficient (IC) defined as $std(|\sum_{i=1}^{N} B1_i^+|)/mean(|\sum_{i=1}^{N} B1_i^+|)$. For technical reasons, only the phase, not the magnitude, of each transmit channel was modulated. The average B1+ efficiency (AvgB1Eff) defined as $mean(|\sum_{i=1}^{N} B1_i^+| \big/ \sum_{i=1}^{N}|B1_i^+|)$ (ranging from 0 to 1) was calculated within the ROIs. A 3D magnitude B1+ map was obtained for each of the three B1+ phase shim sets. MIP images (axial: full thickness; sagittal, coronal: 40mm thickness) were generated from TOF data. SAR values, calculated by the scanner, are expressed as % of the regulatory limit (SAR_{MAX}).

RESULTS. Fig.1 shows magnitude B1+ maps corresponding to the three B1+ shim sets. Quantitative results are summarized in Table 1. The scanner reference voltage was set to obtain a flip angle within the Circle of Willis at the nominal value of 24º. Average B1+ efficiency with setting #1 was 0.51 with a mean (+/-std) α value of 19.6º (+/-5.9º), and IC = 0.3. The corresponding angiogram (Fig. 2a, yellow arrows) shows inhomogeneous background with a higher intensity in the periphery, especially in the frontal and temporal lobes. With setting #2, the homogeneity of α was improved with IC dropping to 0.19 for a mean α value (+/-std) of 21.6º (+/-4.2º), but to the cost of a lower B1+ efficiency (0.23), requiring higher RF voltage. The corresponding angiogram in Fig. 2b shows improved vessel to background ratio (VBR) in the frontal and temporal lobes. With setting #3 the homogeneity was further improved with IC = 0.15 for a mean α value (+/- std) of 21.3º (+/- 3.1º). Compared to setting #1 a better VBR was obtained in the frontal and the temporal lobes. The VBR in comparison to setting #2 was similar in the temporal lobe, but smaller vessels in the frontal lobe were better depicted in setting #2.

DISCUSSION. In this study the potential benefit of using B1+ phase shimming for TOF at 7T was demonstrated: the flip angle standard deviation over the mean was reduced from 0.30 (setting #1) to 0.19 (setting #2) and 0.15 (setting #3) resulting in better VBR and better vessel conspicuity. The cost of higher B1 homogeneity however is a loss in B1+ efficiency which requires higher RF pulse voltage, thus yields higher SAR. When comparing two B1+ strategies (single B1+ solution for all slabs vs. one B1+ solution per slab), it appears that, as expected, some local B1+ defects are more likely to occur with a single solution, as illustrated in Fig. 1 with a signal drop in the right carotid artery present with setting #2 but not in setting #3. However, multiple B1+ solution sometimes result in background discontinuities between slabs, as shown in Fig. 3 in another subject. It also happens that an overall better set of B1+ shim solutions is suboptimal in a specific location; for example, setting #2 provided a slightly better VBR than setting #3 in the frontal lobe. These observations indicate that for clinical applications further B1 shim algorithm characterization is required. Also, the use of phase and *magnitude* B1+ modulation may increase B1+ shim performances. Even though more homogeneous solutions tend to reduce B1+ efficiency and thus increase SAR, the latter limitation can be mitigated by using VERSE pulses. In this study, by using VERSE, SAR was reduced by a factor of 1.6.

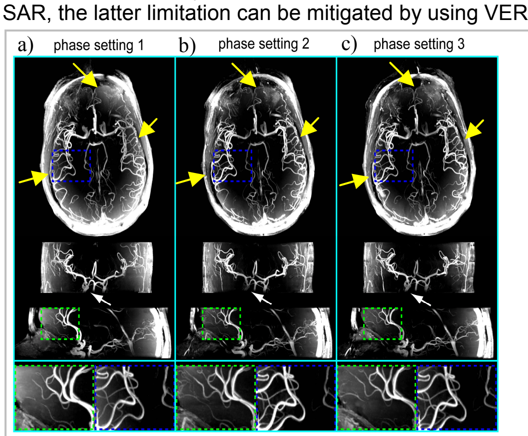

Fig 2 a-c: *resulting MIP images for the 3 B1+ phase settings. The bottom row shows enlarged ROIs from the axial (blue) and the sagital (green) MIP.*

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Table1: *Flip angle, avgB1Eff, RF voltage and SAR corresponding to images in Fig. 2.*

	setting 1	setting 2	setting 3
α mean (std): all slabs	19.6º (5.9º)	21.6º (4.2º)	21.3º (3.1º)
top slab	*22.6º (4.5º)*	*22.6 (4.2º)*	*21.4 (2.3º)*
middle slab	*20.8º (5.1º)*	*22.7 (3.7º)*	*22.1 (4.1º)*
bottom slab	*14.7º (5.2º)*	*19.3 (3.7º)*	*20.3 (2.4º)*
avgB1Eff: all slabs	0.51	0.23	0.24
top slab	*0.57*	*0.24*	*0.27*
middle slab	*0.51*	*0.24*	*0.21*
bottom slab	*0.42*	*0.23*	*0.24*
RF pulse volt. [a.u.]:			
top slab	100%	250%	203%
middle slab	100%	250%	262%
bottom slab	100%	250%	249%
SAR in % of SAR_{MAX}	7%	47%	50%

Fig.3: sagital MIP of the frontal brain of a different subject, acquired with B1+ shim setting comparable to #3. Arrow indicates junction of 2 slabs.