Tissue-dependent asymmetries in the SSFP off-resonance profile

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INTRODUCTION. Steady-state free precession (SSFP) has the unusual property that the signal magnitude and phase are intrinsically sensitive to resonance frequency. This characteristic has been used in a number of contexts to probe tissue content and microstructure. For example, the SSFP frequency profile has been demonstrated to interact with deoxyhemoglobin-induced frequency offsets to create FMRI contrast [1-2]. One intriguing effect that is theoretically predicted, but to our knowledge has not been demonstrated, is the modulation of the shape of the SSFP profile by a frequency-shifted sub-compartment. For a sufficiently large compartment and frequency shift, this should introduce asymmetries to the (theoretically-symmetric) profile in the region of the transition band due to the profile's rapid, 180° phase shift. Here, we report experimental observations of this phenomenon.

METHODS. Balanced SSFP images were acquired using a fully-refocused, 3D stack-of-segmented EPI sequence (i.e., SSFP with several k-space lines each T_R). A series of SSFP images with increasing/decreasing frequency were acquired to cover the entire SSFP profile bandwidth. At the end of each single image acquisition, the RF phase increment was increased/decreased to sweep to the next frequency. Between images, RF pulses were applied without acquisition for 3 seconds to re-establish the steady state. Experiments used T_E/T_R=5.7/12 ms, so that the SSFP profile repeats every T_R^{-1}=83.3 Hz, and acquired 90 images separated by 1 Hz. Other imaging parameters were: α=10°, FOV=22x16.4x6 cm, resolution 2x2x2 mm, 8 lines per T_R, 1516 Hz/pix, scan time 10:29. For the main experiment, three subjects underwent two scans with increasing and decreasing frequency sweep, to establish that the sweep itself did not introduce any asymmetries [3]. Two additional subjects were scanned with two repeats of the sequence, one during inspiration of normal air and the other breathing 3% CO2 to induce mild hypercapnia. Tissue-specific ROIs were defined as follows. A field map was acquired with the same coverage as the SSFP acquisition. A T1-weighted structural was segmented into gray matter (GM), white matter (WM) and cerebrospinal fluid (CSF) using FAST [4]. After alignment to the SSFP data, the fieldmap was masked with its GM, WM and CSF components (limited to 40 frequencies, ±20Hz). For each tissue type, the masked fieldmap was used to select voxels and align their profiles based on their centre frequency. Profiles from each tissue type were combined to generate brain-wide, tissue-specific, mean SSFP signal profiles. A similar procedure was used to segment the WM into different tract ROIs. Tract probability maps from standard-space atlases were affine-transformed to each subject's structural scan and masked by the subject's WM mask to create subject-specific tracts. For all ROIs, the asymmetry was quantified using an Asymmetry Index (AI) defined as the difference in area under the left and right halves of the rectified profile, normalized by the total area. AI thus indicates the asymmetry strength and direction (magnitude and sign, respectively).

RESULTS AND DISCUSSION. Example subject data and ROIs are shown in Fig. 1a-b. The ROI mean data for each tissue type is shown in Fig 1c-e (these curves are the mean data and have not been fit or interpolated). In all cases, both GM and WM exhibit a strongly asymmetric signal profile, with larger profile amplitude at negative frequency offsets. These asymmetries are reproducible regardless of the direction of frequency sweep, and cannot be attributed to disruption of the steady state. Interestingly, the WM profiles exhibit consistently stronger asymmetry than the GM profiles. No consistent asymmetry was found in the CSF data; these ROIs were generally small and resulted in noisy profiles. Data from the hypercapnia subjects is shown in Fig. 2, along with the subjects given two repeats of normocapnia. One subject showed a significant decrease in AI during hypercapnia for both GM and WM, while the other subject had a more modest decrease. These results are suggestive of a dependence of AI on blood oxygenation, but are not yet conclusive. The tract-specific AI values for WM are shown in Fig. 3 (color-coded by subject, both increasing and decreasing sweep are shown). The largest AI was found in the forceps major and minor (corpus callosum), followed by the SLF; the smallest AI was found in the CST and the SOF. Reported FA values in diffusion-weighted MRI exhibit the same relative tract ranking, suggesting that AI may also be a correlate of voxel myelin composition [5].

CONCLUSIONS. We have demonstrated reproducible, tissue-specific asymmetries in the SSFP profile. Preliminary data suggest these may arise from frequency-shifted compartments, but further work will be required to validate this hypothesis. Future work will also investigate faster acquisition (with more rapid sweep) and voxel-wise fitting.

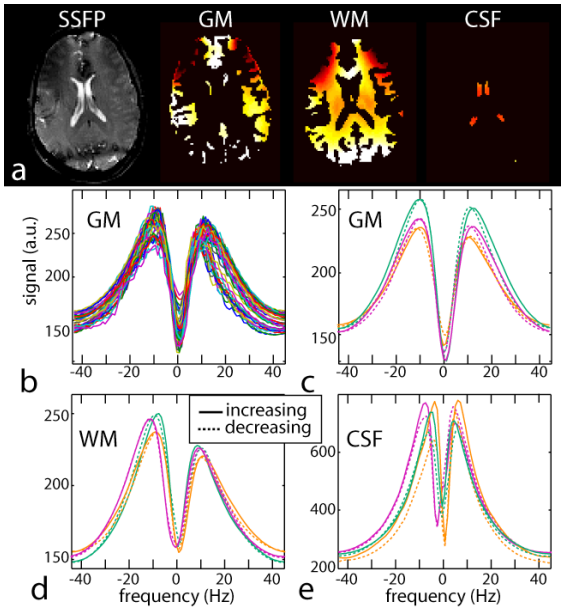

FIGURE 1: (a) SSFP and tissue-segmented fieldmaps. (b) Aligned, mean SSFP profiles for each frequency in a subject. (c-e) Mean SSFP profiles (averaged across all frequencies, color-coded by subject), with increasing (solid) and decreasing (dashed) frequency sweep.

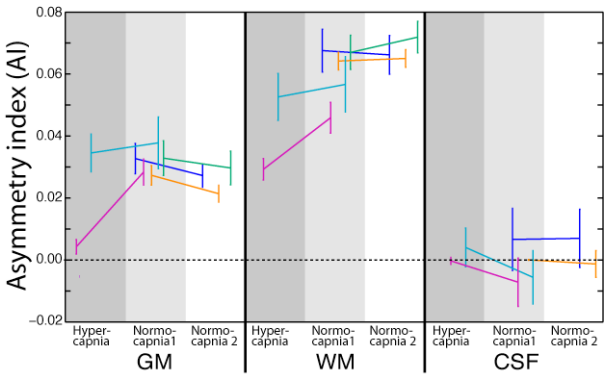

FIGURE 2 (LEFT): AI for the major tissue types, with 2 hypercapnia and 3 frequency-sweep subjects (normocapnia x2). One subject (in pink) has reduced AI with hypercapnia.

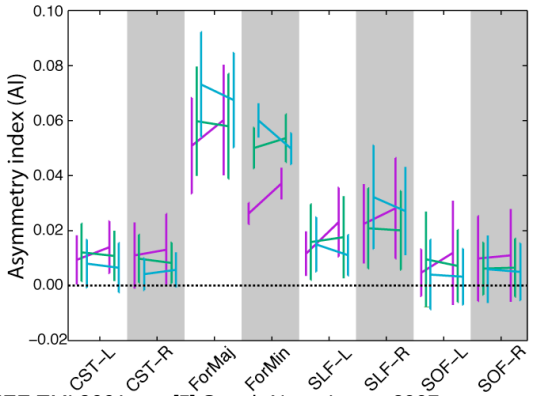

FIGURE 3 (RIGHT): AI for WM tracts, including cortico-spinal tract (CST), forceps major/minor, superior longitudinal fasciculus (SLF) and superior occipital-frontal fasciculus (SOF). The tract-specific AI may reflect myelin content.

[1] Scheffler *NMR Biomed* 2001 [2] Miller *MRM* 2003 [3] Foxall *MRM* 2002 [4] Zhang *IEEE TMI 2001* [5] Snook *NeuroImage* 2007