

Balanced SSFP profile asymmetries are sensitive to white matter tract structure

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INTRODUCTION. Balanced SSFP has the unusual property that the signal is sensitive to resonance frequency. Considering only T_1 , T_2 and diffusion effects, this dependence is predicted to be symmetric with respect to the experimental center frequency (Fig. 3a, “theory”). However, we recently demonstrated that the signal measured *in vivo* is asymmetric (Fig. 3a, points) [1]. For a region-of-interest analysis in the brain, we noted strongest asymmetry in white matter and hypothesized that this effect may relate to tissue microstructure. Theory predicts that asymmetries can result from multiple tissue compartments or non-exchanging water pools that are frequency shifted relative to each other [2]. Here, we present the first maps of SSFP asymmetry, demonstrate excellent consistency of the effect across subjects, and describe several observations that may help elucidate its source.

THEORY. For a single frequency, the SSFP profile is symmetric with respect to frequency; i.e., the signal magnitude is the same for positive and negative frequency shifts (Fig. 3a, “theory”). The entire profile repeats every T_R^{-1} Hz, and, crucially, the signal phase in adjacent repetitions changes by 180° . In a voxel containing multiple frequencies, the signal measured at a given center frequency is the sum of the signal at each frequency weighted by the fraction of spins at that frequency (i.e., the lineshape). If the profile is mapped by repeated measurements at a series of center frequencies, the detected profile is thus the convolution of the SSFP signal profile with the lineshape [2]. For an asymmetric lineshape (e.g., due to frequency-shifted pools), this results in an asymmetric SSFP profile rather than the theoretically symmetric profile. This effect can be large because the 180° phase shift between adjacent bands can cause different parts of the lineshape to phase cancel, effectively placing a large gain on relatively small frequency shifts. The degree of SSFP asymmetry thus contains information about the lineshape and, by extension, the tissue microenvironment.

METHODS. Eight subjects were scanned with a balanced SSFP sequence using a 3D segmented EPI readout (8 PE lines per T_R , 2x2x2mm voxels and 30 slices) [3]. At the end of each volume acquisition, the RF phase increment was increased/decreased to shift to the next frequency, and acquisition was repeated at enough frequencies to cover the SSFP profile (for $T_R=12$ ms, the $T_R^{-1}=83$ Hz profile was covered with 90 images at 1 Hz resolution). Other parameters are given in [1]. To ensure that observed asymmetries were not due to signal transients, three seconds of “dummy cycles” without data acquisition were run before each volume acquisition, and each subject was scanned with both increasing and decreasing frequency. Scan times were relatively long (10:29) due to this conservative approach, and in practice could be shorter (a 5-minute whole-brain protocol is being tested).

RESULTS AND DISCUSSION. Subject asymmetry index (AI) maps are shown in Fig. 1, including scans with increasing and decreasing frequency sweeps. The similarity of these maps indicates that the effect is robust and not due to steady-state transients. Several major white matter tracts are hyperintense, indicating strong asymmetry. Data were aligned to MNI152 standard space, and the mean AI map (n=8) was calculated. This mean was compared to a DTI atlas in white matter by masking $FA > 0.1$ (Fig. 2) or masking the center of white matter tracts (Fig. 3, using TBSS [4]). Although many tracts with high FA also have high AI, these measures are not very well correlated (Fig. 3b). Strongest asymmetry occurs in white matter tracts perpendicular to B_0 (i.e., the x-y plane). For example, the corticospinal tract has low AI but high FA (Fig. 2, arrows). We found strongest correlation to an empirical quantity that reflects both FA and the angle of tract to B_0 : the diffusion in the x-y plane (D_{\perp}) divided by diffusion parallel to B_0 (D_{\parallel}), as shown in Figs 2b and 3a,c. This directional dependence leads us to hypothesize that the asymmetry is sensitive to field offset patterns emanating from frequency-shifted compartments in the white matter. Compartments with different susceptibility in the presence of cylindrical geometry are known to create field offset patterns provided the cylinders are perpendicular to B_0 [5]. This effect is well documented for vessels containing deoxygenated blood, but could also hold for white matter fibers. Note that although our results relate to DTI measures, diffusion effects cannot lead to asymmetries in the SSFP profile.

CONCLUSIONS. SSFP asymmetries are predicted to be sensitive to lineshape asymmetries, with the ability to detect small frequency shifts (~ 10 Hz, see another abstract by our group). We observe strong asymmetries in white matter that are consistent with susceptibility effects related to tract geometry. This effect would relate to white matter microstructure, and constitute a unique contrast for white matter integrity.

- [1] Miller, ISMRM 3068, 2008. [2] Scheffler, NMR Biomed 490, 2001. [3] Miller, MRM 161, 2006.
 [4] Smith, NeuroImage 1487, 2006. [5] Yablonskiy, MRM 749, 1994.

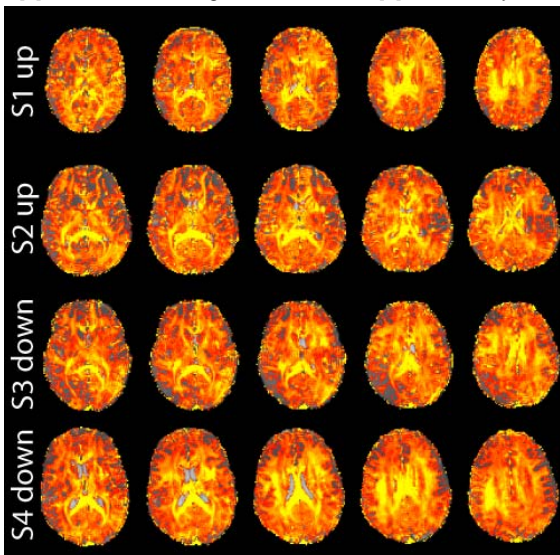


Figure 1: Maps of AI (display range 0-0.2) in four subjects acquired with increasing (“up”) or decreasing (“down”) frequency sweep. $AI = (h_p - h_n)/(h_p + h_n)$, where $h_{p,n}$ is the peak signal for positive (p) and negative (n) frequencies.

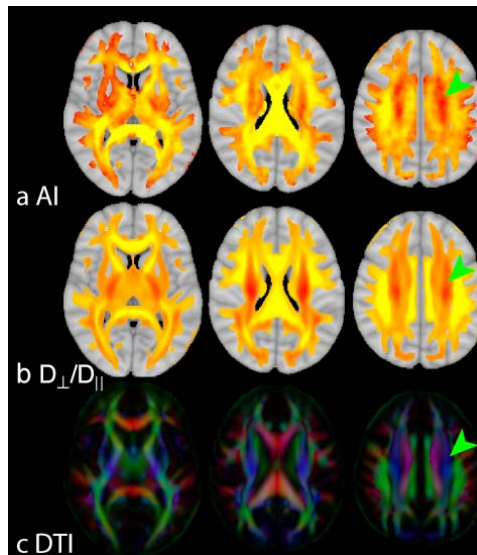


Figure 2: Standard space maps of: (a) mean AI (n=8, AI=0-0.2), (b) tract strength orthogonal to B_0 , (c) principal diffusion direction (x=red, y=green, z=blue). AI is related to both tract direction and FA.

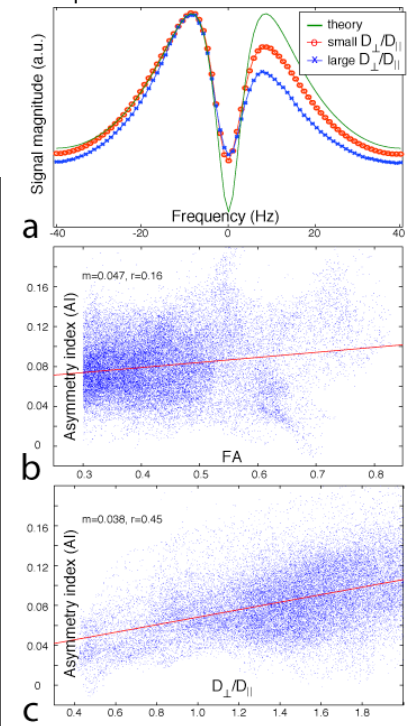


Figure 3: (a) Single-frequency theory and measured SSFP profiles. (b) AI vs FA. (c) AI vs tract strength orthogonal to B_0 . m= slope, r=correlation coefficient.