Imaging weak currents by means of balanced SSFP

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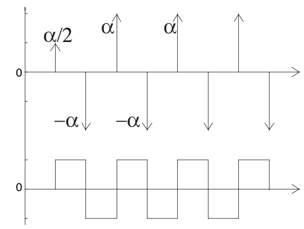
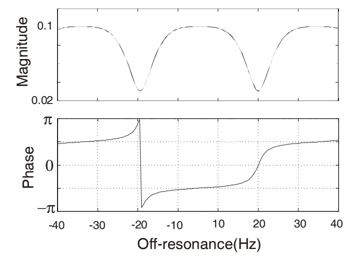
Introduction. Established functional brain MR imaging methods rely on signal generated by changes in cerebral blood flow and are susceptible to factors influencing neurovascular coupling. An ideal imaging method of neuronal activity ought to be transparent to such factors and should measure neuronal activity directly. Several methods for measuring currents generated during neuronal activity in the brain have been proposed previously (e.g. Bodurka and Bandettini, 2002; Biancardi et al., 2004; Chu, R, 2006). Previously used pulse sequences for imaging current-induced spin phase deviations ($\Delta\phi$) include gradient echo and spin echo with echoplanar acquisition. For example, Bodurka et al (1999) used a ΔBz pulse placed immediately after the 90 deg (slice-selective) excitation pulse (and before the refocusing 180 deg pulse in case of spin echo). The phase accumulation time in such a pulse sequence is constrained by echo time TE (usually <100 msec). At higher field (e.g. 3T) T2 and T2* decay times are further foreshortened and thus require even shorter TE (e.g. 30 msec). Despite limited time for phase accumulation afforded by this approach, detected ΔBz values range between 0.1 – 1 nT.



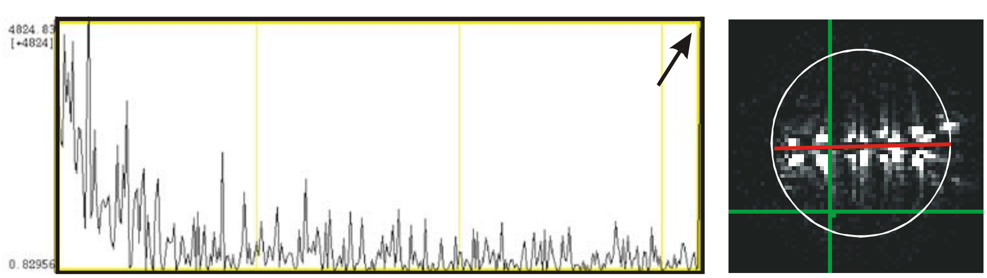
We have explored a potential of a balanced steady state free precession (bSSFP) sequence to detect ΔBz fluctuations. Our method, called PHAse-sensitive Steady State imaging (PHASS, see figure on the right), uses phase cycled bSSFP with RF pulses locked in phase to a current stimulus and relies on an exquisite sensitivity of bSSFP signal magnitude to minute variations in signal phase. Preliminary experiments with an agar current phantom suggest PHASS sensitivity to Bz fluctuations of order 100 pT.

Method. A current-induced magnetic field component Bz that is parallel to B0 can change phase of a spin isochromat according to $\Delta\phi = \gamma\tau\Delta Bz$, where τ is time of phase accumulation. In gradient and spin echo experiments τ = TE, and thus $\Delta\phi$ is limited by TE<100ms. On the other hand, the magnitude of bSSFP signal is highly sensitive to off-resonance with signal reduction occurring around 1/TR offsets (see figure on the right). When the current-induced ΔBz alternates between 2 states, an oscillating equilibrium is reached. Signal detection then is a function of a separation between the dual states, and depends on static off-resonance. Maximum separation between the sates is reached close to the signal minimum where the rate of signal change as a function of offset is maximum. An agar phantom with relaxation properties imitating those of gray matter with inserted copper wire was used to explore sensitivity of PHASS. Range of currents explored was 1mA – 10 uA. Bz induced by a long wire falls of as an inverse function of distance from wire $Bz = u_0 I/2\pi x$ (I is current). For example, for I=0.1mA , Bz(4cm) = 0.5 nT.



A balanced SSFP sequence with 1- or 2-shot spiral and echoplanar readout was used (TE=2.9ms, TR = 17-34msec, nreps = 500, FOV=12-24cm, 64x64 matrix, 3-4mm slice thickness). In order to explore sensitivity of the PHASS signal to static off-resonance, a static linear gradient along X axis was applied, which resulted in a characteristic banding artifact. The power spectrum of signal fluctuations around the banding artifact were explored as a function of distance from the wire.

Results. A typical pattern of current-induced fluctuations is shown in the figure below (right). The image represents coefficients of power spectrum (left) at the frequency of current fluctuations. The stripy pattern is a result of banding artifacts produced by application of the linear shim gradient along the X axis. Locations of fluctuation maxima correspond to minima of the SSFP off-resonance function. The magnitude of fluctuations drops inversely with distance from the wire (indicated by red horizontal line in the middle of the phantom outline), as predicted by application of Biot-Savart law to a straight conductor. The power spectrum of a voxel at crosshairs is shown on the left. The arrow indicates power at the current alternation frequency. The left figure shows a power spectrum of a time series in a voxel at a distance of ~4 cm from the wire at the center of a phantom (right). The magnitude of the ΔBz fluctuations is in the voxel approximately is 0.5nT. Our preliminary data indicate that magnetic fields as small as 50pT are potentially detectable using this approach.



Power spectrum

Discussion. Our results suggest that the sensitivity of bSSFP to ΔBz fluctuations is highly inhomogeneous in space with maximum sensitivity occurring around SSFP signal minima. An imaging pulse sequence using PHASS techniques will require careful placing of excitation frequency on the off-resonance values resulting in minimum bSSFP signal. Application of multiple excitation frequencies might be necessary for exhaustive coverage of an imaging slice, as suggested by Miller et al (2003).

References.

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