Flow compensation in non-balanced SSFP

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Introduction. Non-balanced steady-state free precession sequences (SSFP-FID and SSFP-echo) are gradient-spoiled pulse sequences that provide high signal even in presence of long T_1 values, because the transverse magnetization is not completely incoherent by means of radiofrequency spoiling. Contrary to balanced SSFP sequences they do not suffer from off-resonance banding artifacts, making them more suitable for clinical applications in some regions. However, these sequences are extremely sensitive to flow and motion, because of spoiler gradients that produce large first moments. The steady state is perturbed by moving isochromats and this phenomenon results in artifacts and signal loss, mostly noticeable in the presence of moving tissues with long T_2, like the cerebro-spinal fluid around the brain. In this work, we present a theoretical explanation for this phenomenon by means of numerical simulation of the Bloch equations, and completely flow-compensated SSFP-FID and SSFP-echo implementations that eliminate this source of artifacts.

Materials and Methods.

Simulations. A conventional SSFP-FID sequence with TE/TR of 3/6 ms and a flip angle of 60° was simulated by applying the matrix form of the Bloch equations to a population of 100 spins with T_2 values ranging from 25 to 1000 ms and T_1 values ranging from 500 to 2000 ms, and applying at the end of each TR a global phase shift with maximum amplitude of ±pi/12, with three different time behaviors: a sine wave with a period of 1s, a sine wave contaminated by 20% of the amplitude of random noise, and a completely random phase. In order to simplify the simulation, the phase accumulation at acquisition time was neglected. The amount of oscillations in the signal acquired at TE was evaluated as the ratio between the signal variation and the mean signal over 1000 TRs in the steady-state.

Sequence implementation. A custom three-dimensional pulse sequence was implemented with the following characteristics: full first moment compensation at acquisition and at the end of TR for every k-space line, and adjustable intra-voxel dephasing before and after acquisition. The dephasing was set to 2π after acquisition for the SSFP-FID sequence and to 2π before acquisition for the SSFP-echo sequence. A custom iterative gradient optimization algorithm was developed in order to obtain the most efficient flow-compensating waveform for every k-space position.

Experimental setup. In vivo experiments were performed on a healthy volunteer with a 1.5T whole-body scanner (Avanto, Siemens Medical Solutions, Germany) with the following parameters: TE/TR 6/14ms, bandwidth 790 Hz/px, matrix size 192x144x104, resolution 1.5x1.5x1.5mm^3. Various flip angles were tested ranging from 15° to 90°. Conventional non-compensated SSFP-FID and SSFP-echo acquisition with matching parameters were acquired for comparison.

Results. Simulations showed that in presence of time-varying phase accumulations between TRs, the signal amplitude in the steady-state is and reduced in mean and oscillating, by a factor that depends on the nature of the phase perturbation (fig. 1). The amount of oscillations appearing in the steady-state is increasing with T_2 of the considered tissue (fig. 2). The *in vivo* results showed a significant improvement in the image quality (fig. 3), where no artifact contamination was present in the brain parenchyma and no ghosting artifacts are appearing outside the desired region. Eye motion is still creating some residual blurring artifacts. Similar results were obtained for SSFP-echo images.

Discussion. In addition to conventional flow artifacts deriving from phase accumulation at acquisition time, SSFP sequences are also subject to steady-state disruption when a phase is accumulated after the acquisition. As shown in the results, for realistic SSFP-FID and SSFP-echo imaging parameters, the steady-state is perturbed more when moving tissues with long T_2 are imaged. This is visually apparent in images of the brain, where artifact contamination due to CSF in the parenchyma is prone to obscure pathologies. Random eye movement is still creating some blurring artifacts, which can be confined outside the brain with a wiser choice of the imaging slab. As a conclusion, complete flow compensation is an effective method to eliminate blurring artifacts due to motion, at the cost of longer TR and therefore longer acquisition times.

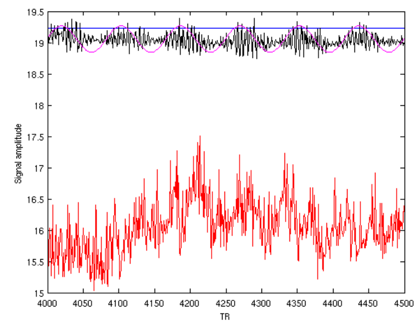

Fig. 1: Simulated SSFP-FID signal in the steady-state (T_1=500ms, T_2=200ms). Blue trace: unperturbed signal; magenta trace: sinusoidal perturbation; black trace: noisy sinusoidal; red trace: random phase.

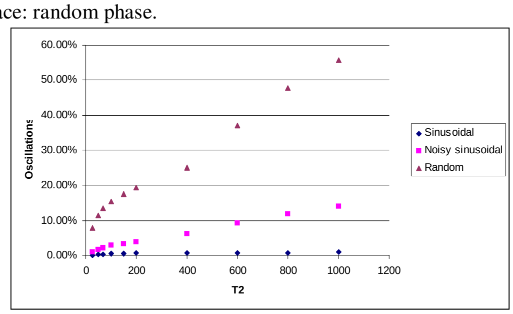

Fig. 2: Amount of oscillations in the steady-state for different T_2 relaxation times and different perturbations (T_1=1500ms).

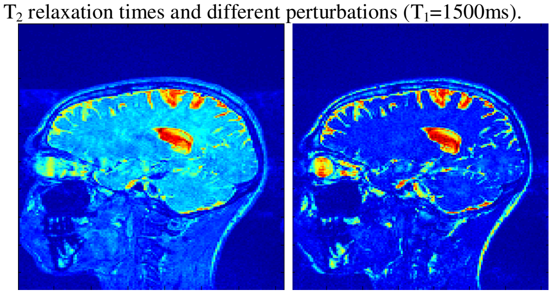

Fig. 3: Comparison between non-compensated (left) and compensated (right) SSFP-FID imaging of the brain.