An interleaved center frequency acquisition method in transition-band SSFP fMRI: Increased spatial off-resonance coverage

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Introduction

Transition-band SSFP fMRI [1-3] is a recent functional imaging method that enables high-resolution studies by fully utilizing the scan time with the SNR efficiency of the balanced-SSFP sequence. However, the functional contrast of this method can only be measured at a narrow spectrum (~3 Hz at 1.5T) near on-resonance frequency. As a result, to cover a desired spatial region, the functional experiments were repeated with slightly shifted center frequencies. Typically, three repetitions were performed for a region-of-interest study [2] and eleven repetitions for a whole brain coverage [3] depending on the field distribution and the result of shimming. Although this repeating scheme showed successful results, it sometimes requires narrower center frequency shifts due to the temporal drifts and the subject condition in each experiment might influence the results. Therefore it is beneficial to interleave different center frequencies within one volume acquisition time in one experiment so that different spatial coverage undergoes the same experimental conditions. Here we present an interleaved center frequency acquisition method to increase the spatial coverage in SSFP fMRI.

Methods

In a steady-state sequence, the magnetization from the previous RF excitations is not crushed but reutilized to increase SNR efficiency. However, as the residuals of the previous magnetization still exist, any sudden scan parameter changes in the following TR can cause abrupt signal change in the existing steady state resulting in a signal transient. In small-flip-angle balanced SSFP where the flip angle is substantially small (4º) compared to the relaxation time (TR = 10.4 ms), the magnetization profile can be modeled as the summation of T2 decay [4]. Therefore, the time constant for this transient period is T2. Since the transient period causes imaging artifacts, it is important to reduce this period to increase the readout duty cycle. Three different schemes [(a) abrupt frequency change, (b) linear frequency increase, (c) abrupt frequency change with the transverse magnetization crushed] were simulated to compare the transient effects. The simulations were performed by solving the Bloch equation, the simulation parameters were TR = 10.4 ms, flip angle = 4º, center frequency shift (or RF phase change) = $2 \cdot \Delta f$ = 6 Hz (22º in RF phase), T1 = 780 ms, T2 = 80 ms. The center frequency was shifted by changing the transmit RF and receiver phase cycle. For experiments, a high-resolution 3D stack-of-spiral trajectory balanced-SSFP sequence (resolution = 2x2x2 mm³, TR = 10.4 ms, TE = 0 ms, FOV = 22 cm, flip angle = 4º, nslice = 10, ninterleaves = 8) was ordered in three different center frequencies (Δf = -3Hz, 0Hz +3Hz, one volume acquisition time = 1 (sec) x 3 (frequencies) = 3 sec) over 2:15 minutes. Between the frequency transitions, a period of linear center frequency increase (16 TR lengths) was allocated to mitigate the transient effects. The k-space was covered from the outermost sides to the center in the kz direction to further reduce the imaging artifacts. A field map was generated and the shimming was targeted to the visual cortex area. The stimulus was a flashing checkerboard (15 sec on / 15 sec off). For comparison, single center frequency experiments were performed at three different center frequencies (Δf = 0 Hz, +3 Hz and –3 Hz). The transition time (16 TRs) in the previous experiment was not utilized to match the SNR with the previous method. Since the volume acquisition time is 1 second, three times the amount of the previous samples were acquired. The time series were resampled such that only one sample out of three consecutive samples was selected in the same order as in the interleaved experiment. The scan time was 6:45 minutes (2:15 (minutes) x 3 (frequencies)). All scans were performed on a 1.5 T GE EXCITE system using a standard head coil. Analysis was performed using FEAT (FSL, Oxford) with no spatial smoothing. Each experiment was inspected for subject motions and showed no significant motion. The different center frequency data was analyzed individually and combined to generate the mean z-statistic activation maps [3] with a threshold of $z > 2.05$ in both methods.

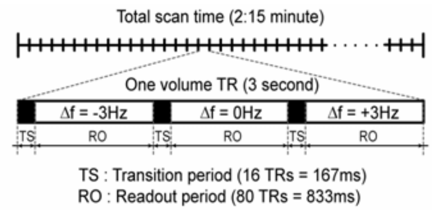

Figure 1. Conceptual block allocation

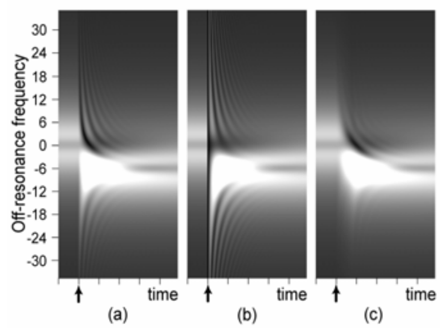

Figure 2. Simulation results: (a) abrupt change, (b) Mxy signal crushed, (c) gradual change

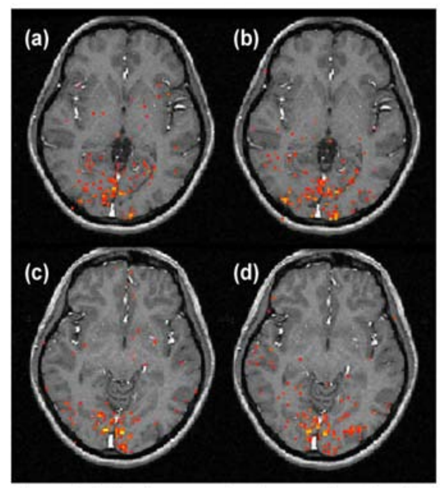

Figure 3. Activation maps: (a,c) conventional method (three experiments with different center frequencies). (b,d) interleaved center frequency method (one experiment with three different frequencies in each TR). Upper figures 6th slices and lower figures 2nd slices

Results

Figure 2 shows the simulation results of three different schemes. The linear center frequency shift during the transition period shows decreased signal oscillation in the off-resonance area compared to the others. In the experiments, no significant imaging artifacts were observed. The activation maps are largely similar in the two methods (Fig. 3). The slight difference might have originated from the field drift during the experiments, short scan times and other noise effects [1].

Discussion and Conclusion

A new method that interleaves different center frequencies in each volume acquisition time is proposed. This method provides three times wider off-resonance coverage while maintaining a reasonable number of slices (nslices = 10) and TR (one 3D time with three frequencies = 3 sec). As a result, a ROI study is possible without any repetition. This method also provides more reliable data because the effects from time varying conditions are reduced compared to the repetitive methods. The sequence of the interleaved center frequencies could be step-wise continuous (-Δf, 0, Δf, 0, -Δf, 0, Δf, …); in this case, one center frequency has two different previous conditions producing slight oscillations in the time-series.

Reference

[1] Miller KL. MRM 50:675-683 (2003) [2] Lee J. ISMRM, p120, (2005) [3] Miller KL. ISMRM, p2686, (2005) [4] Lee J. ISMRM , p2346, (2005)