Respiratory navigators in non-stop cine cardiovascular SSFP imaging

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Introduction
Steady-state free precession (SSFP, FIESTA, true-FISP, BFFE) is strongly established in cardiovascular imaging for its reliable blood-to-myocardium contrast and high SNR in cardiac cines. For some applications, the continual RF pulses for SSFP conflict with the use of other sequence "preparation" pulses, such as respiratory navigators which may be useful for improving the alignment of the series of end-expiratory breath-holds used for short-axis stacks, eliminating breath-holds for some patients, or acquiring longer studies such as 3D. Other "preparations" such as saturation tag pulses have applications in myocardial and blood bolus-tracking, or inversion pulses in myocardial viability imaging. For SSFP applications requiring preparation pulses, existing methods stop the regular RF α-pulses, typically using α/2 "flip-back" (1) to preserve the precessing magnetization along z, and continue after the preparation pulses by applying another α/2. Techniques of linearly-incrementing start-up angles (LISA) (2) and catalysation (3) optimize accurate re-establishment of the SSFP. This abstract describes a new method that avoids stopping the SSFP, by interleaving the preparation pulses into the continuing train of SSFP α RF pulses, maintaining the condition that the position-related phase shifts due to gradient pulses are rephased in the TR interval from one SSFP RF pulse to the next.

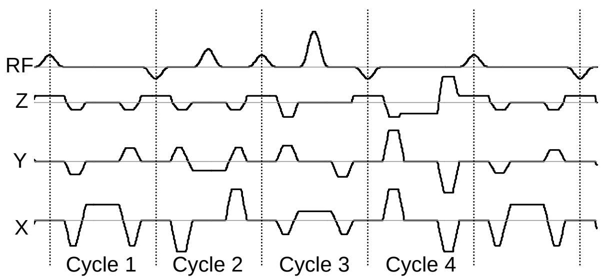

Figure 1

Method: The new SSFP navigator ("non-stop method") was compared with α/2-navigator-α/2 ("flip-back method") in volunteer subjects. A continuous 2D SSFP cine sequence was modified, with the navigator after each ECG R-wave, followed immediately by segmented phase-encoded cine acquisition with no dummy cycles between (also known as stabilization or preparation cycles) the navigator and the first cine frame. The two navigator methods were compared for artifacts in transverse breath-hold SSFP cines, such as phase-encode ghosting. Navigator data was reconstructed by 1D-FFT and compared. For this evaluation of the feasibility of the non-stop method, the navigator data was used to monitor breath-hold quality, not for respiratory gating. It was therefore expected that artifacts were mainly caused by SSFP disturbance. Free-breathing data was also acquired, to test detection of respiratory motion by the navigator. In each RR interval, the conventional navigator was obtained by a frequency-encoded echo in the head-foot direction through the right diaphragm along a column formed by intersecting 10mm slice-selective 90 and 180 RF pulses. For the non-stop method, the 90 and 180 pulses and the navigator data acquire were inserted between α-pulses of the SSFP cine sequence without modifying their timing or slice-selectivity (Figure 1, during transverse SSFP imaging, Z=head-foot, Y=anterior-posterior phase-encoding, X=left-right frequency-encoding). Cycle 1 shows a normal dummy cycle of the SSFP sequence: having just detected an R-wave, the next cycle 2 applied a navigator's coronal 90 slice-selection, cycle 3 applied its sagittal 180 slice-refocussing, and cycle 4 its data acquire along the head-foot Z axis. (The navigator 90 was coronal for clarity of waveforms in Figure 1, but oblique *in-vivo* to avoid the heart). The gradient pulses for the navigator (slice-selections, frequency-encode, and spoilers after the navigator RF pulses) were complicated by the need to rephase their area within each cycle to maintain the SSFP, which also limited the navigator data acquire's resolution to 2mm. No attempt was made to rephase also the velocity phase shifts during each cycle, and navigator cycles tended to lose this desirable property of SSFP slice-select and frequency-encode waveforms for cardiovascular imaging. The SSFP sequence parameters were conventional: TR=3.6ms, TE=1.8ms, 11 phase-encodes per cine frame per RR interval, raw data matrix 256 FE by 143PE over 400mm by 275mm FOV, FA=60°.

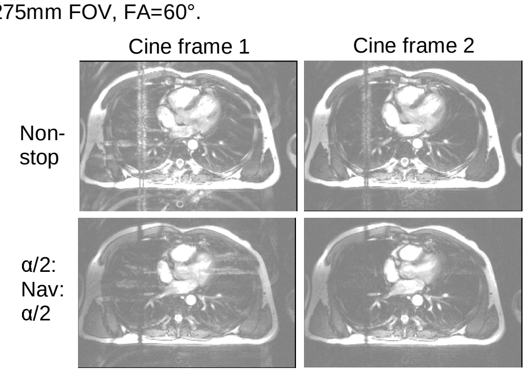

Figure 2: Comparison of SSFP artifacts after navigator

Results and Discussion: Both methods (Figure 2) showed ghosting in the phase-encode direction which decayed to zero by the 3rd frame. In frame 1, ghosting by the non-stop method was more severe than in the flip-back method. The frames are earlier in cines using the non-stop navigator method because it was shorter than the flip-back method in this work. The ghosting in both methods was altered by centre-frequency tuning, but its pattern was reproducible. By replacing the navigator cycles with empty cycles of SSFP (no FE or PE pulses), it was found that ghosting occurred even after 1 empty cycle of SSFP. After 2 empty cycles, ghosting was *less* than after 1 empty cycle (an effect which persisted less prominently in higher even numbers vs odd numbers of empty cycles). Ghosting was also reduced if identical waveforms were inserted into 2 successive SSFP cycles, and therefore the non-stop navigator repeated the navigator data readout cycle (data unused). The navigator traces obtained by the two methods were similar. Fig.3 demonstrates detection of breathing motion by the non-stop navigator.It is well-known that SSFP is sensitive to residual phase shifts of each cycle. Although the first-order gradient area was no longer zero in some navigator cycles, ghosting was from all tissue, not only moving blood. The navigator was applied at a cardiac timing with slow flow, and could equally well run in late diastole, so that SSFP stabilisation would affect less important cine frames. Inevitable sources of small imperfections in the gradient area rephasing are likely to be involved, especially if the waveforms differ sharply between the navigator cycles and the SSFP imaging and dummy cycles. The ghosting caused by insertion of just one empty cycle into SSFP indicated that sudden changes are more of the problem than an error which is similar in successive cycles. (Even without navigators, imaging was improved in the segmented cine SSFP sequence using block-ky coverage which uses more gradually changing PE waveforms than interleaved ky-coverage). The effects of the different unrephased Maxwell gradients of the navigator cycles compared with the SSFP imaging and dummy cycles were found negligible for the isocentre transverse plane used. The ghosting pattern was not affected by <10% changes in the gradient pre-emphasis amplitudes and decay-constants. Non-segmented cine acquisition phase images were used to examine the phase variations of each cycle's data acquisition (which led to the ghosting in segmented acquisitions), with adjustable gradient area rephasings and SSFP α-pulse phases within each individual SSFP navigator cycle and following cycles; no methodical approach to reduce the reproducible pattern of ghosting was yet found, and no empirical adjustments were found useful. The ghosting was expected to change with image plane location and angles, so oblique image planes were not attempted.

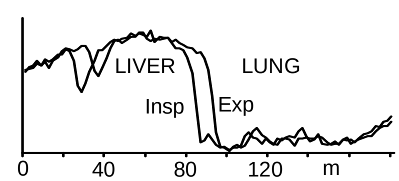

Fig.3: Non-stop navigator (2mm resln.)

Conclusion: Non-stop SSFP preparation is feasible in-vivo, but unlikely to be useful until the stability problem can be solved.

References (1) Scheffler K et al, MRMed 45:1075-80. (2) Deshpande VS et al, MRMed 49:151-7. (3) Hargreaves BA et al, MRMed 46:149-58.