Flow-Insensitive, Motion-Compensated Balanced Steady-State Free Precession Imaging

O. Bieri[1], J. Leupold[2], G. Laub[3], K. Scheffler[1]

[1]Department of Medical Radiology, MR-Physics, University of Basel, Basel, Switzerland, [2]Department of Radiology, Section of Medical Physics, Freiburg, Germany, [3]Siemens Medical Solution, Los Angeles, CA, United States

Introduction. For conventional balanced steady state free precession b-SSFP pulse sequences employing gradient reversal echoes and short repetition time (TR << T2), the time integral of each of the three gradients is zero within each TR interval. Following Zur et.al. [1], a steady state within an infinite train of rf-pulses can only be established, if the precession angle

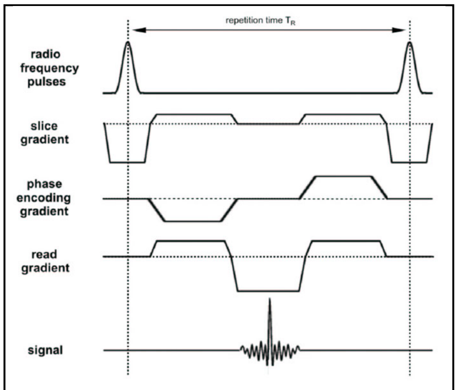

Fig. 1: 2D b-SSFP pulse sequence. In this scheme all gradients but PE have nulled zeroth and first order moments.

$$\phi(n) = \gamma \int_{t=0}^{n\cdot TR} \left\langle \mathbf{G}(t) \middle| \mathbf{r}(t) \right\rangle dt$$

is constant for all TR time intervals (for the sake of simplicity, magnetic field inhomogeneities are ignored). Hence, in the b-SSFP scheme, the phase increment for a spin moving with constant velocity, $\mathbf{r}(t)=\mathbf{r}_0+\mathbf{v}t$, equals

$$\Delta\phi_{x,y,z}(n) \equiv \phi_{x,y,z}(n+1) - \phi_{x,y,z}(n) \overset{!}{\underset{b-SSFP}{=}} \gamma \cdot v_{x,y,z} \int_{t=0}^{TR} G^{(n)}_{y,z(3D)} \cdot t \cdot (t) dt \neq 0$$

In contrast to other SSFP imaging sequences such as GRASS, FAST and others, motion sensitivity in b-SSFP sequences is drastically reduced due to its completely balanced gradient scheme [1]. However, changing phase encoding (PE) gradients may lead to significant signal loss, due to non-constant phase increment,

$$\Delta\Delta\phi_{x,y,z}(n) \overset{!}{\underset{b-SSFP}{=}} \gamma \cdot v_{x,y,z} \left(\int_{t=0}^{TR} G^{(n)}_{y,z(3D)} \cdot t \cdot (t) dt - \int_{t=0}^{TR} G^{(n-1)}_{y,z(3D)} \cdot t \cdot (t) dt \right) \neq 0$$

Consequently, for full motion compensation not only zeroth order gradient moments, but also first order gradient moments must be nulled in the b-SSFP pulse sequence.

Methods. Minimal time-consuming motion compensating gradients for phase & slice (3D) encoding have been calculated on the fly during sequence execution (figure 2). Due to the time-consuming “bipolar” gradient waveform for motion compensation, however, TR compared to standard b-SSFP sequences is increased. The additional time required for motion compensation depends on the strength of the actual PE gradient. Overall data acquisition time can thus be minimized using an optimized timing for each PE step and its corresponding motion compensation gradient separately. Therefore, short TR can be used in the center of k-space while a somewhat increased TR (41%) has to be applied for the outer parts of k-space. With a conventional, linear PE trajectory the resulting, motion compensated b-SSFP sequence exhibits a smooth, linearly increasing and decreasing change in TR, and total acquisition time is only increased by 16% compared to conventional b-SSFP.

Results. 3D measurements have been performed on a flow-phantom (a flexible tube was attached like a coil along a bottle of water) using gadolinium-doped water (250µM) (1x1x1.6mm^3 resolution, 256x256x96 matrix). Figure 2 compares motion-compensated b-SSFP with standard b-SSFP in a reference scan (without flow)and with flow along both PE directions. Obviously, without flow both sequences result in identical images (the slightly higher signal intensity for the motion-compensated sequence is most likely due to the varying TR). In contrast, signal loss due to motion (0.8m/s laminar flow) is clearly visible in the uncompensated standard b-SSFP sequence, whereas the motion compensated sequence proves to be motion inert (the slight shading is due to inflow of unmagnetized spins from bottom to top). The smooth variation of TR of the compensated sequence did not produce visible image artifacts, as expected from frequency shifted b-SSFP sequences [2].

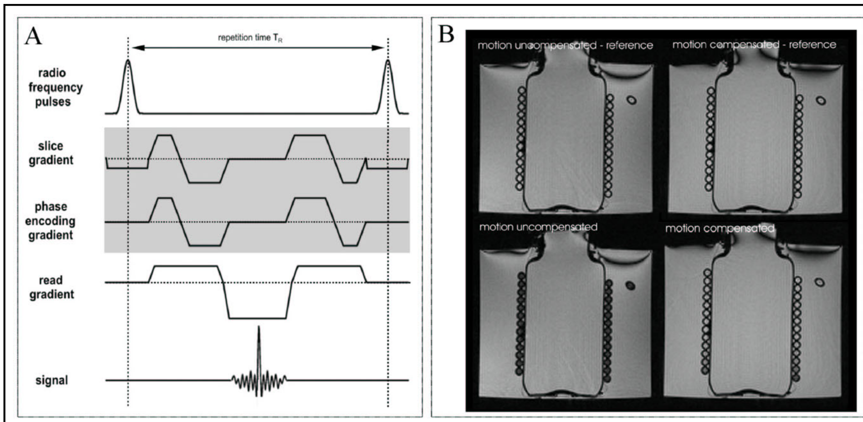

Fig.2: (A) 3D motion compensated b-SSFP pulse sequence. (B) standard b-SSFP without flow (upper left), with laminar flow (lower left), motion compensated b-SSFP without flow (upper right) and with flow (lower right).

Discussion. The motion/flow sensitivity of conventional b-SSFP can produce a significant signal loss for flow along uncompensated PE direction. Compensation or nulling of first moments within TR preserves the required phase coherence of consecutive excitation pulses, which is essential to produce the full b-SSFP signal. The presented sequence was not flow compensated between excitation and echo, which might result in an additional flow-related phase of the acquired echo and spatial misregistration. However, for b-SSFP phase compensation along excitations is more important compared to unbalanced or rf-spoiled sequences..

References.

[1] Zur Y., Wood ML, Neuringer LJ. Motion-insensitive, steady-state free precession imaging. MRM 1990;16:444-459.
[2] Foxall DL. Frequency-modulated steady-state free precession imaging. MRM 2002; 48:502-508.