Phase-cycled multiband SSFP imaging with CAIPIRINHA for efficient banding removal

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Purpose

Balanced SSFP (b-SSFP) is a widely used fast imaging technique characterized by its high SNR efficiency and the unique T_2/T_1 contrast. Its main limitation is the banding artifact resulting from its sensitivity to field inhomogeneity. One common approach for banding reduction is to perform multiple acquisitions with different phase cycling [1], which inevitably lengthens the total imaging time. Multiband (MB) b-SSFP using the CAIPIRINHA [2] technique has recently been proposed [3-4] to accelerate b-SSFP imaging, however modulating the phase of the MB excitation pulses not only results in shift of the aliased imaging slices in space, as expected, but also shift in the off-resonance profiles in b-SSFP. In this work, we present a novel technique for efficient banding removal in b-SSFP by utilizing MB imaging with CAPIRINHA for acquiring multiple phase-cycled images within the same imaging time as a standard single b-SSFP acquisition. Initial feasibility study was carried out on the brain, which can be expanded to SSFP imaging of body organs.

Methods

Figure 1 shows the proposed scheme with MB factor of 3. Three slices are excited simultaneously with a spatial shift of FOV/3 (red), 0 (blue) and –FOV/3 (green) along the phase encoding direction, respectively, which result in $2\pi/3$, 0, $-2\pi/3$ shift in their off-resonance profiles (Fig 2). With sequential acquisition of 6 MB-3 slices, the center 4 slices will have the full 3 phase-cycled images, which then can be combined for banding reduction. The same scheme can be applied for other MB factors. In general, for N MB imaging slices and a factor of M acceleration, the center N-(M-1) slices will have the full phase cycled images.

Four healthy volunteers (21±3 years old) were imaged on a 3T Siemens Tim Trio system using a 32-channel head receiver coil. Eight axial slices were acquired using MB b-SSFP CAIPIRINHA with MB factor of 2 (with FOV/2 shift), 3 (with FOV/3 shift) and 4 (with FOV/4 shift), respectively. For comparison, standard b-SSFP scan was performed with identical slice positioning. The rest of the imaging parameters were: FOV=256mm², matrix size=192x192, slice thickness=5mm, distance factor=150%, TR=4.2 and 8.4ms, TE=TR/2, flip angle=30º, number of ramp pulses=24 and 48. Aliased MB slices were reconstructed using slice-GRAPPA [5] algorithm with a kernel size of 3x3. Phase cycled images were combined using both maximum intensity and sum of squares.

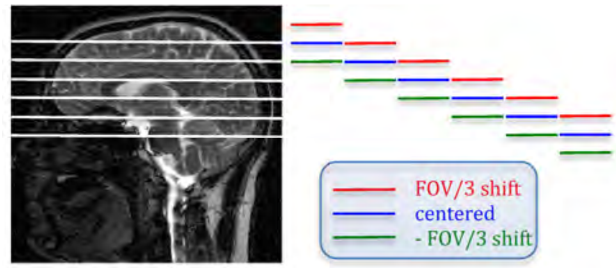

Figure 1. Schematic diagram of a MB-3 b-SSFP acquisition. Each set of red, blue and green lines represent 3 slices that are excited and readout simultaneously. Red, blue and green represent slices with a FOV/3, centered and -FOV/3 shift along the phase encoding direction, or $2\pi/3$, 0, $-2\pi/3$ shift in their off-resonance profiles.

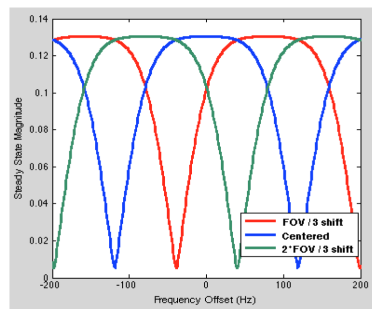

Figure 2. MB-3 b-SSFP off-resonance profiles for different phase cycling, i.e., FOV shift. Red, blue and green slices match those in Fig. 1. Three phase-cycled images can be combined to achieve a more homogenous signal profiles.

Results

Figure 3 shows multiple un-aliased phase-cycled images acquired using b-SSFP with MB-2 (top), MB-3 (middle) and MB-4 (bottom) accelerations. It can be seen that different phase cycling leads to variation in the banding behavior, e.g., shifts in banding location (see arrows). In Fig. 4, maximum intensity (left column) and sum-of-squares (right column) combined images are shown for MB-2 (top), MB-3 (middle) and MB-4 (bottom) b-SSFP acquisitions, respectively. Overall banding artifact is suppressed effectively in all scenarios. Visually, least amount of residual banding artifact is seen in MB-4 case. Hence, the performance of banding removal improves as the number of phase cycling or MB factor increases. Overall, maximum intensity yielded better band reduction than sum-of-squares combination scheme.

Conclusions and Discussions

We introduced an efficient approach for rapid banding removal in b-SSFP using phase-cycled MB imaging. The advantage of the presented technique is the reduction in the scan time by a factor of M as compared to conventional phase cycling approach, although SAR is increased by the MB factor. We also found a large number of ramp pulses (48) is necessary for b-SSFP signal stabilization with MB-4. Future work includes expansion to imaging other body organs, and more advanced image combination schemes to further reduce the residual banding.

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References

[1] N. Bangerter, et al., MRM, 2004, p.1038-47. [2] F. Breuer, et al., MRM, 2005, p. 684-91. [3] D. Stab, et al., MRM, 2011, p.157-64. [4] M. Blaimer, et al., MRM 2013, p.974-80. [5] K. Setsompop, et al., MRM, 2012, p.1210-24.

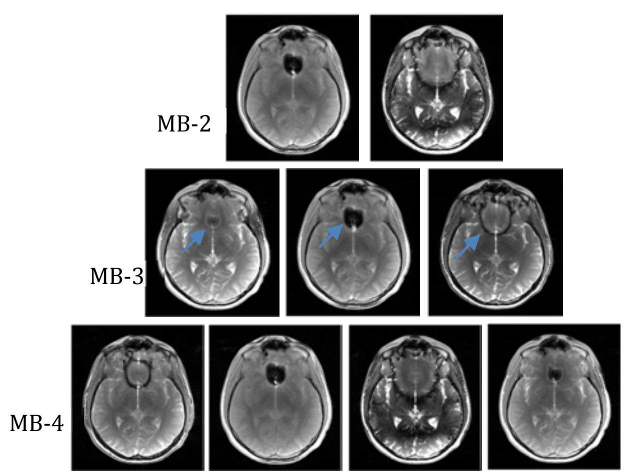

Figure 3. Example Un-aliased multiple phase-cycled images acquired using b-SSFP with MB-2 (top), MB-3 (middle) and MB-4 (bottom) acceleration. The location of banding artifacts shifts between different phase cycling (arrows).

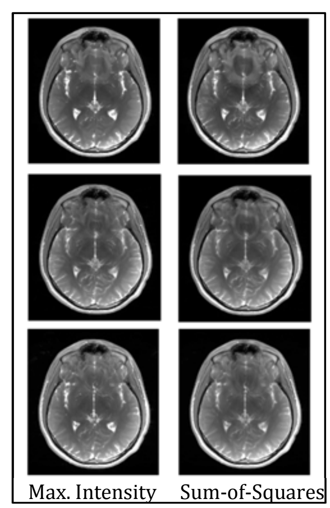

Figure 4. Banding removal by maximum intensity (left) and sum-of-squares (right) image combination.