

Mitigation of bSSFP Flow Artifacts using Partial Dephasing

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Synopsis

We show that partial dephasing mitigates artifacts from through-plane flow near dark bands in balanced SSFP. A 30°-60° range in the phase accrual during a TR is created over the voxel by slightly unbalancing the slice-select rephaser. The effects of partial dephasing on the spectral profiles for various flow rates were simulated, and the simulations were validated in a flow phantom. By decreasing the strength and non-linearity of the signal's dependence on through-plane flow rate, partial dephasing mitigates the transient artifacts caused by pulsatile flow. In volunteer studies, it noticeably decreased artifacts in all of the phase-cycled cardiac cine datasets acquired.

Purpose

Balanced steady-state free precession (bSSFP) is commonly used for cardiac imaging due to its high SNR and desirable myocardium-blood contrast but is sensitive to off-resonance. In slice-selective acquisitions, through-plane flow near a steady-state stop-band (or "near-band") can cause strong enhancement from out-of-slice spins and artifacts propagating in the phase-encode direction from the band.¹⁻³ In addition, these artifacts make multiple-acquisition bSSFP, which is normally used to get banding-free bSSFP images, challenging in the heart since the band falls in the blood pool in at least one of the phase-cycled component images.⁴⁻⁶ Here, we propose using partial dephasing⁷ to mitigate near-band flow artifacts, preventing them from corrupting other parts of the image and aiding multiple-acquisition bSSFP in the heart.

Methods

In partial dephasing, a 30° to 60° range in the phase accrual during a TR is created over the voxel by slightly unbalancing the slice-select refocusing lobe before the RF pulse.⁷ In standard bSSFP, at the bands, spins that flow out of the slice remain in-phase, causing a manyfold increase in the signal.¹ We hypothesized that partial dephasing would decrease this out-of-slice coherency by causing spins that have flown out to experience a different amount of phase accrual each TR. By therefore decreasing the strength and non-linearity of the dependence of the signal at the bands on the through-plane flow rate, partial dephasing would mitigate the transient artifacts caused by pulsatile flow.

To test this, the spectral profiles for various flow rates with a fully-balanced sequence and with 30° and 60° of partial dephasing were determined using Bloch simulations similar to those used by Markl and Pelc.¹ The parameters were: TR=3.5 ms, TE=1.75 ms, T1=1000 ms, T2=150 ms (in-slice), and T2*=75 ms (out-of-slice). Spins were moved through the slice profile of a 60° TBW-2 Hamming-windowed sinc with FWHM of 6 mm. Static spins and flows up to 100 cm/s, corresponding to 58.3% spin replacement per TR, were simulated. The level of inconsistency of the spectral profile across different flow rates was used as an indication of how much variable flow during image acquisition will cause the signal to vary, thus leading to transient-related artifacts.

To validate the simulations, we imaged a slice through a constant flow phantom with and without 60° of partial dephasing with 36 different RF phase-cycling amounts. Imaging was done at 1.5 T with 4.6 ms TR and 2.0 ms TE. Various slice thicknesses (8, 6, 4, and 2 mm) resulted in different spin replacement percentages. To get empirical spectral profiles, the mean signal in an ROI in the tube, normalized by slice thickness, was plotted versus phase-cycling amount. The average velocity in the ROI ranged from 28.8 to 35.1 cm/s during the scan session.

Cardiac cine images of axial slices of six volunteers were acquired with 0°, 30°, and 60° of partial dephasing to assess if partial dephasing mitigates near-band flow artifacts. Images with 180° and 0° phase-cycling were acquired with 3.4 ms TR, 1.4 ms TE, and 6-8 mm slice thickness. The Y linear gradients were offset from the optimal shim to create increased off-resonance.

Results

Bloch simulations indicate that the strength and non-linearity of the dependence of the near-band signal on the through-plane flow rate in fully-balanced SSFP is substantially reduced by partial dephasing – with 30° and especially 60° of partial dephasing, the spectral profiles in Figure 1 morph smoothly as a function of the flow rate. Therefore, simulations suggest that partial dephasing may mitigate near-band flow artifacts while maintaining bSSFP's high SNR. The spectral profiles measured in the flow phantom (Figure 2) validate the simulations. With partial dephasing, the images of the lumen at frequencies surrounding the band do not have the flow artifacts seen without partial dephasing (Figure 3).

In vivo, partial dephasing removes the artifacts seen in standard bSSFP images (Figure 4). The root-sum-of-squares-combined⁸ multiple-acquisition images with partial dephasing do not have obvious artifacts, in stark contrast with the images without partial dephasing (Figure 5).

Discussion and Conclusion

Flow phantom and in vivo images indicate that partial dephasing alleviates the near-band flow-related artifacts to which bSSFP is sensitive. In our experience, artifact mitigation was robust, with a marked improvement in several cardiac phases of all of the cine datasets acquired. Sixty degrees of partial dephasing suppressed artifacts slightly more robustly than 30° but may broaden stop-bands, so the optimal amount should be investigated.

Although it does not address the signal nulls, partial dephasing prevents flow artifacts from dark bands from corrupting other parts of the image. It therefore facilitates multiple-acquisition bSSFP in the heart, which is banding-free.

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Figures

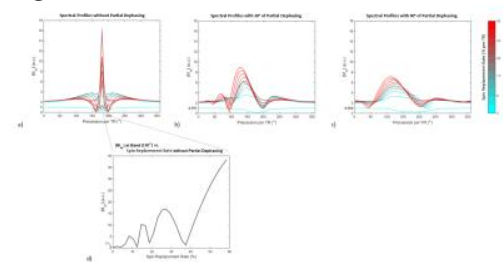


Figure 1: Simulated spectral profiles of spins with various velocities without partial dephasing (a), with 30° of partial dephasing (b), and with 60° (c). From blue-green (static spins) to red (71.4 cm/s, or 41.7% spin replacement), line color indicates faster flow. Signals are normalized by the signal of static, on-resonant spins in fully-balanced SSFP. The plots are centered on the stop-band. Without partial dephasing, the stop-band signal is a highly non-linear function of the flow rate (d), while with 30° and especially 60° of partial dephasing the signal at all frequencies changes more smoothly as a function of flow velocity.

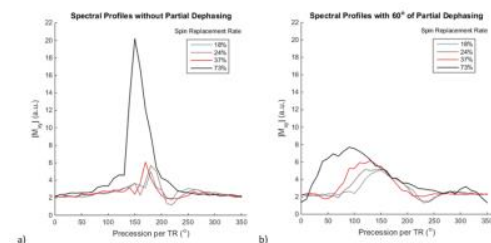


Figure 2: Measured spectral profiles without partial dephasing (a) and with 60° of partial dephasing (b). Spin replacement rates are calculated assuming the mean of the ROI velocity measurements during the scan session (31.8 cm/s). With the exception of the black lines, which are for a higher spin replacement than shown in Figure 1, the plot colors follow the colorbar in Figure 1. The measured profiles look similar to the corresponding simulated profiles, validating the Bloch simulations.

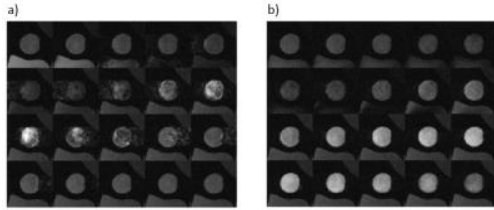


Figure 3: Phase-cycled SSFP images of the flow phantom lumen, with approximately 37% spin replacement per TR, at frequencies surrounding the stop-band. From left to right and then top down, the RF phase-cycling of each of the 20 images is offset by 10° from the previous. In the dataset without partial dephasing (a), the central images have transient-related flow artifacts that the images with 60° of partial dephasing (b) do not have.

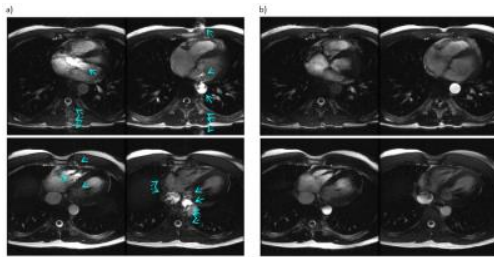


Figure 4: Systolic SSFP images of two subjects (top and bottom rows) with 0° and 180° RF phase-cycling. The fully-balanced SSFP images (a) all contain regions of very hyper-intense signal (solid arrows) and transient-related artifacts propagating in the phase-encode direction (dotted arrows) that are mitigated in the analogous images with 60° of partial dephasing (b).

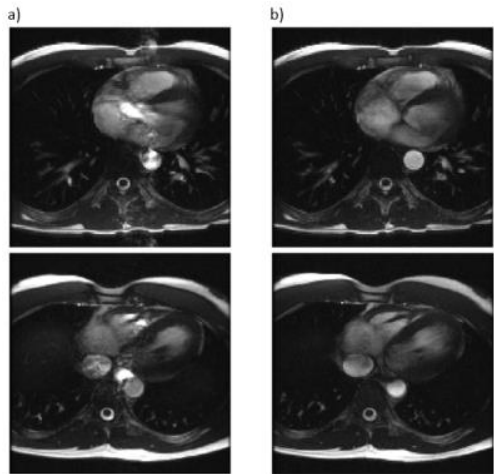


Figure 5: Root-sum-of-squares combinations of the images in Figure 4. The top and bottom rows correspond to the two subjects in Figure 4. In the images without partial dephasing (a), the flow artifacts from the component images persist in the combined images. In contrast, the combined images with 60° of partial dephasing (b) are free of these artifacts, as well as not having the signal nulls of the single-acquisition component images in Figure 4.