Pulse sequences for phase-contrast SSFP imaging from a single steady-state

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Introduction: Steady-state phase contrast (SSPC) flow imaging offers high phase-signal-to-noise ratio at reduced scan times compared to gradient echo techniques [1-3]. However, due to the sensitivity of SSFP to eddy-current-induced phase variations from one TR to the next, SSPC velocity measurements have until now been limited to establishing two separate steady-states (one for each value of the gradient first moment), and hence acquiring each image separately. This produces phase-contrast measurement errors in regions where the two images are not in perfect spatial alignment, and requires careful switching between the two steady states. We introduce two different, complementary, approaches to SSPC imaging, each based on the formation of a single steady state.

Methods and Results: Experiments were performed on a GE Signa 3T EXCITE HD system (40 mT/m gradient amplitude; 150 T/m/s slew rate) using the RTHawk real-time imaging platform [4]. Method "A" uses the principle of readout gradient inversion [2,3] to encode flow within a single TR. The pulse sequence timing diagram is illustrated in Fig. 1. An image is formed from each of the three echoes, and the phase contrast, velocity, and local off-resonance are given by

$$PC = \frac{1}{2}\angle\left(im_{\mathrm{Echo1}} \times im^{*}_{\mathrm{Echo2}}\right) + \frac{1}{2}\angle\left(im_{\mathrm{Echo3}} \times im^{*}_{\mathrm{Echo2}}\right), \quad v = \frac{PC}{\gamma(\mathrm{m1}^{+} - \mathrm{m1}^{-})}, \quad \Delta\omega_{off-res} = \frac{\angle\left(im_{\mathrm{Echo3}} \times im^{*}_{\mathrm{Echo1}}\right)}{t_{Echo3} - t_{Echo1}}$$

Note that the third echo is needed to compensate for off-resonance-induced phase-accrual between echoes. Measurements in a uniform static ball phantom obtained with a transmit/receive head coil (Fig. 1, blue box; FOV = 20 cm; voxel size 1x1x5 mm^3; flip angle $\alpha = 50^o$; α, $-\alpha$ RF cycling) demonstrate the robustness of this approach to local off-resonance. In Fig. 1, we corrected for phase shading along the readout direction, caused by gradient/DAQ timing error.

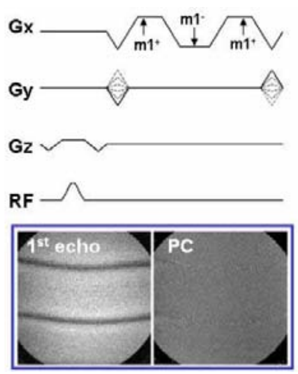

Fig.1: *Method A: Readout gradient inversion within a single TR. Readout plateaus are adjusted to achieve the desired VENC. Blue box: Static phantom results. Gradient shims were adjusted to introduce linear off-resonance along the phase-encode direction (vertically in the figure).*

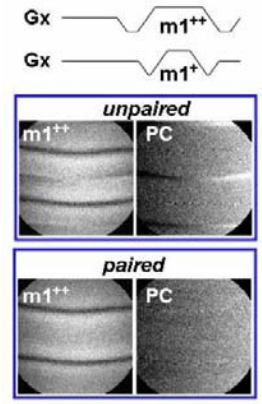

Fig. 2: *Method B: Interleaved gradient waveforms with different flow encoding but a common steady state. An unpaired acquisition gives distortions in both magnitude and phase (top blue box), which are mitigated by pairing the velocity-encoding gradients (bottom blue box).*

Method "B" achieves larger velocity-encoding (VENC) values at reduced TR values by interleaving two different gradient waveforms that produce different first moments at the center of kx-space. Here we use the two readout gradient waveforms shown in Fig. 2 to achieve in-plane velocity-encoding along the readout direction. The top blue box in Fig. 2 shows that alternating between these two waveforms every TR ($m1^{++}$–$m1^{+}$–$m1^{++}$–$m1^{+}$ ordering) introduces distortions in both magnitude and phase. To reduce these eddy-current-induced distortions, we propose the use of "VENC pairing", analogous to the principle of phase-encode pairing introduced by Bieri *et al* [5]. Each velocity-encoding gradient is executed twice (scanning adjacent phase-encode lines), after which the other gradient waveform is played twice, and so on, to produce $m1^{++}$–$m1^{++}$–$m1^{+}$–$m1^{+}$ ordering. The lower blue box in Fig. 2 shows that this approach greatly reduces eddy-current-induced steady-state distortions.

Fig. 3 shows ECG-gated measurements of the carotid bifurcation using a 4-channel neck coil (20 cm FOV; 1.3x1.3x5 mm^3 voxel; $\alpha = 40^o$; α, $-\alpha$ RF cycling; VENC = 150 cm/s). Results using a standard (GRE) PC acquisition with bipolar VENC gradients ($\alpha = 15^o$) are also shown. In addition, preliminary testing was done using a constant-rate flow phantom, and in a pulsatile carotid phantom from PBD (not shown) [6].

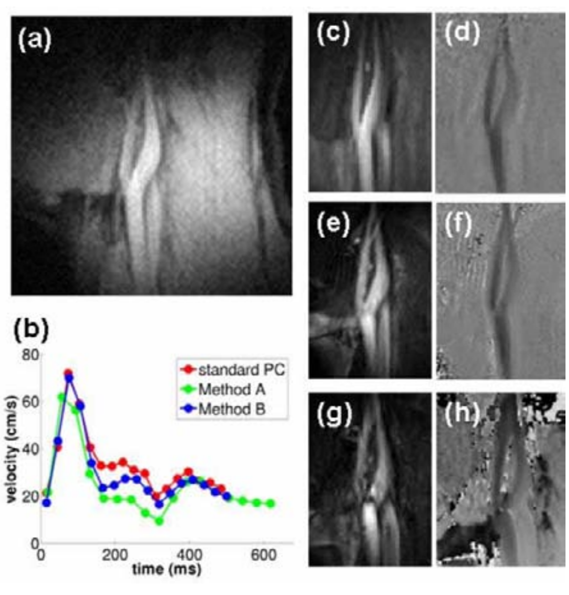

Fig.3: *Phase-contrast imaging of the carotid bifurcation. (a) Magnitude reference image (fat-suppressed GRE acquisition) (b) Gated flow measurements obtained just below the bifurcation. Magnitude (c,e,g) and phase-contrast images (d,f,h) obtained with (c-d) standard (GRE) imaging (TR = 4.9 ms), (e-f) Method B (TR = 5.0 ms), and (g-h) Method A (TR = 6.2 ms).*

Discussion: A disadvantage of Method A is the relatively long TR compared to conventional (non-interleaved) SSPC measurements using gradient inversion [2,3], which increases the severity of SSFP banding artifacts. However, it is important to realize that Method A also measures local off-resonance (as well as flow), and that such quantitative off-resonance measurements can be used to place any anatomical region-of-interest safely away from SSFP banding artifacts, or to exclude pixels during retrospective analysis. In addition, Method A can be used in conjunction with wideband SSFP [7] in order to reduce the sensitivity to off-resonance.

Although VENC pairing appears to be a robust approach for reducing magnitude and phase artifacts near the center of the SSFP pass-band, the degree of artifact suppression depends on the details of the two interleaved gradient waveforms. In particular, incomplete artifact suppression using VENC pairing is observed when alternating the sign of the readout gradient [2,3]. Finally, we note that the principle of VENC pairing can be applied to any pair of gradient waveforms that encode flow along any axis.

Conclusion: Rapid, single steady-state phase-contrast measurements using half the total number of RF excitations is possible using multiple gradient inversions within each TR. When interleaving different waveforms, VENC pairing suppresses steady-state magnitude and phase distortions.

References: [1] Overall *et al*, MRM 2002;48:890-898. [2] Markl *et al*, MRM 2003;49:945-952. [3] Grinstead *et al*, MRM 2005;54:138-145. [4] Santos *et al*, Proc. IEEE EMBS, 26th Annual Meeting. [5] Bieri *et al*, MRM 2005;54:129-137., [6] Phantoms By Design, Inc., Bothell, WA. [7] Nayak *et al*, Proc. ISMRM 13th Scientific Meeting (2005), p2389.