Multi-Directional High Moment Encoding in Phase Contrast MRI

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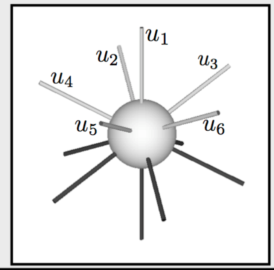
Introduction: Signal to noise ratio gains in low VENC phase contrast MRI are limited by the ability to successfully unalias phase measurements that fall outside the -π to π interval. The ability to unalias phase measurements on a per pixel basis is limited by errors in the measurements due to noise and signal biased phase [1]. The method presented in this work provides more time efficient gains in SNR compared to a well known 'three-point' method previously presented by Lee et al [2]. Simulations are used to characterize both methods.

Figure 1: Orientations for six velocity sensitive directions that make the vertices of a regular icosahedron. The white vertices represent the positive flow direction and the black are the negative.



Methods: The proposed method is to measure multiple velocity sensitive directions at a low VENC. Measurement directions are distributed as uniformly as possible. Figure 1 shows an example of measurement orientations for six directions representing the vertices of an icosahedron. The velocity sensitive directions ($\mathbf{u}_i$)measure the component (v_i) of the spin velocity ($\mathbf{v}$) parallel to each direction, where i=0...N.

$$v_i = \mathbf{v} \cdot \mathbf{u}_i \qquad (1)$$

The vectors $\mathbf{u}_i$ are not completely orthogonal; each measurement contains some shared information with its neighbors. This information is used to unwrap the aliased measurements by forcing consistency of the solution with each measurement. In the absence of noise or phase bias the measured velocity component in each direction (m_i) is assumed to be the actual velocity component (v_i) plus an integer velocity offset (due to phase aliasing) which results in an additional integer multiple (k_i) of 2VENC in the measurements.

$$m_i = v_i + 2VENCk_i \qquad (2)$$

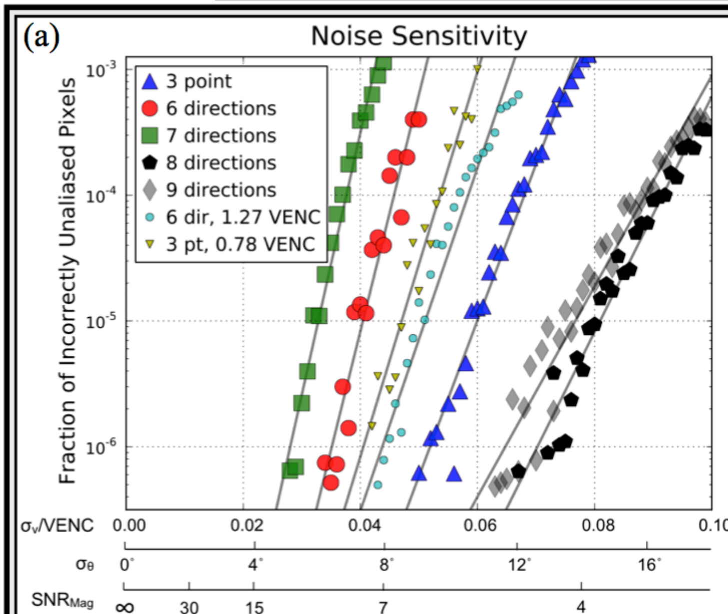
Velocity estimates ($\mathbf{v}_e$) are calculated via matrix inversion of all direction vectors ($\mathbf{U}$=[$\mathbf{u}_1$...$\mathbf{u}_n$]) applied to the measurement vector ($\mathbf{m}$) minus the solution vector ($\mathbf{k}$).

$$\mathbf{v_e} = \mathbf{U}^{-1} \cdot (\mathbf{m} - 2VENC\mathbf{k}) \qquad (3)$$

The consistency error (E) of each solution vector is the sum of squared difference between the back projected estimated velocity ($\mathbf{v}_e$) and the measured components minus their respective offsets.

$$E = \sum_i^N (\mathbf{v_e} \cdot \mathbf{u}_i - (m_i - 2VENCk_i))^2 \qquad (4)$$

Noise sensitivity and output SNR were determined by Monte Carlo simulations. The corresponding solution **k** to the minimum consistency error was found via brute force. Orientations for 6 to 9 measurement directions were found using a charge repulsion algorithm [3]. The 3 point method was simulated with a high/low VENC ratio of 4; the 2-NEX method with a VENC of 4.



(b)

Method	Relative SNR	Relative Time	Relative SNR_{eff}
2 NEX	1.00	7	1.00
3 point	2.81	7	2.81
6 dir	3.60	7	3.60
7 dir	3.69	8	3.45
8 dir	3.75	9	3.31
9 dir	3.83	10	3.21

Figure 2: Noise sensitivity (a) and output SNR efficiency (b) determined through Monte Carlo simulations. The input velocity deviation is normalized by VENC. SNR efficiencies are normalized by the 2-NEX method results.

Results: The failure rate (figure 2a) of each method (in terms of velocity noise (σ_v) by VENC, phase noise (σ_θ), and image SNR) is shown to be sharply related to the level of input noise. All of the methods require a minimum image SNR between 5 and 15. Figure 2b shows the relative SNR efficiency of each method normalized by time. The 6 direction method has the highest SNR efficiency and requires a phase noise less than about 6°, which corresponds to an image SNR of about 8. The 8 direction method has the third highest SNR efficiency and has a phase noise threshold of about 12° requiring an image SNR of about 5. Each additional measurement direction produces diminishing SNR returns.

Conclusion: The SNR time efficiency of the proposed method is about 3.6 times greater than a comparable time averaging implementation (2-NEX) and about 1.3 times greater than the three-point method at the same gradient moment.

References: [1] Pipe, MRM, 49:543, 2003; [2] Lee, MRM, 33:122, 1995; [3] Hasan, JMRI, 13:769, 2001

Acknowledgements: This work was supported by AHA grant 10GRNT4630004.