Optimization of Short-TE Phase Contrast Flow Quantification

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Target audience: MRI physicists - flow measurement.

Purpose: Phase contrast (PC) flow measurement in high-velocity turbulent jets is difficult due to intra-voxel dephasing signal loss. Signal may be improved by shortening the echo time TE by using the slice-selection gradient for flow encoding [1], but this has the disadvantage that Velocity ENCoding (VENC) and slice thickness (ST) become coupled. Secondly, gradient timing hardware imperfections relative to the slice-section RF pulse and the radial-UTE ramp sampling can result in errors during off centre imaging. We present an optimized radial k-space PC flow measurement sequence incorporating (i) inversion of alternate slice-selection and flow-encoding gradients (+/- flow encoding), (ii) correction of gradient moment during slice selection, (iii) TE minimized slice-select and flow-encoding gradient design with three pulses G1 (slice-select), G2 and G3, (iv) independent selection of ST and VENC parameters, and (v) flow-compensated half-echo readout, limited to the gradient flat-top for improved robustness with in-plane slice shifts.

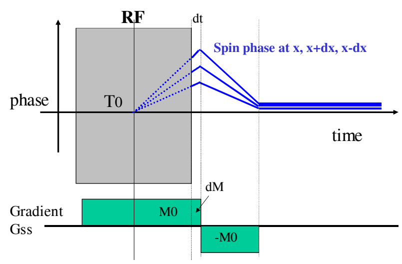
Methods: A prototype PC flow GRE sequence was modified for reduced TE. The radial readout on the gradient flat-top acquires an echo with maximum asymmetry, with the k-space center acquired after 16 samples. The coupling of ST with VENC was overcome by the use of a three-pulse design in combination with an algorithm to minimize TE: the ST and a fixed excitation bandwidth of 4 kHz prescribed the amplitude and duration of the slice-select gradient (G1). With the M0 and M1 for G1 known, G2 and G3 were optimized for duration (D2, D3) and amplitude (A2, A3) to minimize TE while maintaining M0=0, and M1=VENC/2. In some cases where ST and VENC are positively correlated, the optimal solution is a two-pulse design with D2 and A2 set to zero.

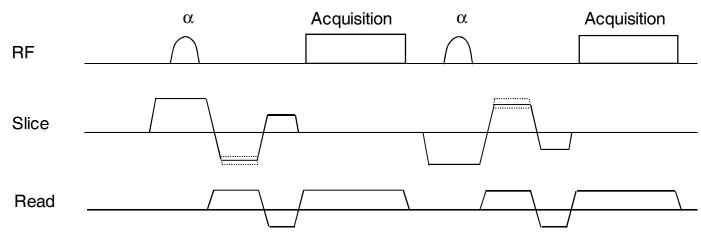
If the RF modulation for off centre imaging is not perfectly aligned with the slice-selection gradient, the signal contains a phase ϕ that is proportional to the signed gradient amplitude and RF modulation frequency and is thus proportional to the slice off-centre shift (Figure 1). This phase is also present in standard PC flow sequences with separate through-plane flow-encoding gradients without slice-selective inversion, but is removed by subtraction of the flow-encoded and flow-compensated complex data. Our method inverts the slice-select gradient to achieve symmetric flow encoding in both the positive and negative directions, thus inverting ϕ, which during complex signal subtraction leads to a phase error of 2ϕ.

Imaging was performed on a 3T scanner (MAGNETOM Skyra, Siemens AG Healthcare Sector, Erlangen, Germany): BW 558 Hz/pixel, FOV 300mm, acquisition 128 (readout)x 127 (spokes). We measured the phase error in a constant flow phantom in the axial plane at various off centre positions and implemented a delay correction by calculating an equivalent adjustment to the amplitude A2 (Figure 2) to ensure constant phase off centre (Figure 3).

Figure 1 (left): Gradient misalignment with the RF pulse leads to position dependent phase.

Figure 2 (right): Inverted slice select generates +/- flow encoding, dotted lines show timing correction implemented as a change to G2 amplitude.

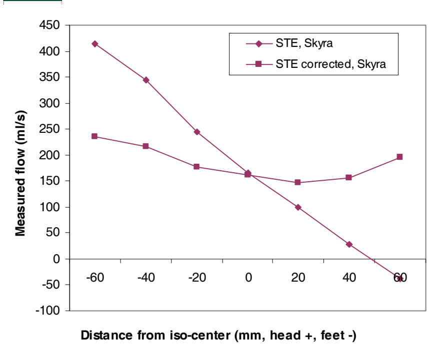


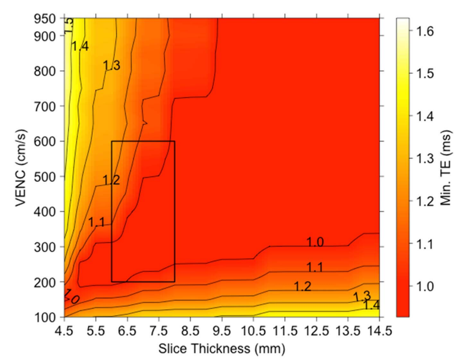


Results:

Figure 3 (left): Flow measured for 170 ml/s with and without 0.2 µs correction of velocity-encoding gradient delay (note no background phase correction was performed).

Figure 4 (right): TE (ms) achieved with different ST and VENC. TE<0.97 ms is limited by the flow-compensated readout. Typical clinical parameters for jet imaging are highlighted in the rectangular region.





Discussion: The incorporation of an experimentally determined timing correction to align the slice-select gradient with the off-center modulation of the RF excitation removed the linear dependency of signal phase on distance from the iso-centre. Residual variations are likely due to eddy currents and B0 offsets, requiring background phase correction. Due to the larger gradients required, low VENC and thin slices are the most challenging for TE minimization, but the use of an optimized three-pulse design allowed any VENC or ST to be chosen independently, which was not possible with a two pulse design. The flow compensated readout was the limiting factor when both VENC and ST increase together, with a minimum TE of 0.97 ms on the Skyra. Typical TR was 3.19 ms per spoke of k-space data.

Conclusion: The timing correction during slice-selection improved the off iso-centre performance of flow sequences using +/- flow encoding with alternating slice select gradients. The use of a three pulse encoding scheme together with an optimization algorithm enabled ST and VENC to be varied independently and for the TE to be reduced to < 1.5 ms, and < 1.0 ms for most clinical VENC and ST settings. The short TR allowed for rapid imaging. This sequence is expected to represent a significant improvement in performance for reducing intra-voxel signal loss when measuring high-velocity turbulent jet flow.

Reference: [1] O'Brien KR et al. MRM 2009;62:626-636.