Reduction of Eddy Current-Induced Velocity Offsets in Phase Contrast MRI

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INTRODUCTION – Phase contrast MRI (PC-MRI) is subject to numerous sources of error including eddy currents (*1*), Maxwell terms (*2*), gradient field distortions (*3*), and chemical shift (*4,5*), each of which decreases both quantitative accuracy and clinical confidence in the reported measures. The dominant theme for optimizing PC-MRI protocols has focused on minimizing the echo time (TE) and repetition time (TR), which reduces signal loss due to T_2^* and improves the temporal resolution or reduces breath hold times. For many applications, however, other sources of error dominate and neither SNR nor temporal resolution lead to significant quantitative errors. Recent work has shown that chemically shifted perivascular fat corrupts the phase estimate in PC-MRI and can lead to ~10% errors in flow measurement (*4*). These errors can be reduced to clinically insignificant levels with the use of a high bandwidth (HBW) and in-phase TE (TE_{IN}). The impact of HBW+TE_{IN} on eddy current induced phase errors, however, is not known. Post hoc correction methods for eddy current errors pose a challenge clinically, making eddy current reduction by means of sequence optimization advantageous. We tested the ***hypothesis*** that the chemical shift optimized PC-MRI protocol (HBW+TE_{IN}) has reduced eddy current-induced velocity offsets compared to the standard low bandwidth minimum TE (LBW+TE_{MIN}) clinical protocol used at our institution. If eddy current errors are sufficiently reduced, then post hoc corrections can be obviated.

THEORY – Time-varying magnetic fields (e.g. velocity encoding gradients) induce eddy currents in conducting structures. Eddy currents create unwanted magnetic field gradients, which lead to phase errors in velocity measurements because they don't subtract in phase difference processing. Eddy current-induced velocity offsets are difficult to predict and necessitate correction to obtain absolutely quantitative results. Several eddy current correction methods have been proposed, which include image-based techniques (*6,7*) and phantom calibration (*1,8*). These techniques are respectively either inaccurate because they require extrapolation or inefficient because they require additional measurements. Figure 1 shows a trapezoidal gradient (G(t)) (i.e. half of a velocity encoding waveform) and slewrate (dG/dt) waveforms and a simple mono-exponential eddy current-induced field ($B_e(t)$), which results in an eddy current-induced velocity offset ($\phi_e(t)$) at the time of the echo (TE). The use of HBW-TE_{IN} results in dead time in the sequence after velocity encoding because $TE_{IN}>TE_{MIN}$ ($\Delta TE=2.15$ms). Therefore, the equal-and-opposite eddy current phases (ϕ_e^+ and ϕ_e^-) are more alike at TE_{IN} than at TE_{MIN}, thereby off-setting each other and resulting in reduced eddy current-induced velocity offsets in PC-MRI at TE_{IN} compared to TE_{MIN}. For small values of the eddy current time constant, τ, dead time will play a minimal role because the eddy currents build up and decay very quickly. Conversely, for large values of τ, eddy currents build up and decay very slowly, thus the role of dead time will again be minimal. For intermediate values of τ, the dead time in the HBW-TE_{IN} sequence may lead to a reduction in eddy current-induced velocity offsets relative to LBW-TE_{MIN}. Thus the chemical shift optimized HBW+TE_{IN} PC-MRI protocol should have reduced eddy current-induced velocity offsets compared to the standard LBW+TE_{MIN} protocol.

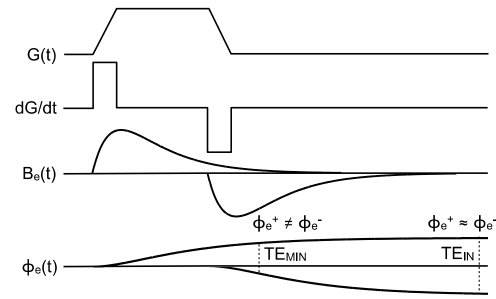

Figure 1. For a trapezoidal gradient waveform, G(t), eddy current fields, $B_e(t)$, build up due to gradient slewing, dG/dt, and decay. The difference in the integrated eddy current phase, $\phi_e(t)$, will be less at TE_{IN} vs. TE_{MIN} ($\phi_e^+ \neq \phi_e^-$ at TE_{MIN} whereas $\phi_e^+ \approx \phi_e^-$ at TE_{IN}).

METHODS – Eddy current induced velocity offsets were measured in a stationary gel phantom (97.85% water, 2% hydroxyethyl cellulose, 0.1% copper sulfate, and 0.05% sodium azide). The phantom was placed at isocenter of a 3T scanner (Siemens Trio, VB17A). Measurements were made using a cine spoiled gradient echo velocity-encoding sequence: TE_{IN}/TR=4.92/6.91ms and TE_{MIN}/TR=2.77/4.26ms, 128×88 matrix, 2.8×2.8×6mm^3 voxels, 15° flip angle, 399 (LBW) and 814 (HBW) Hz/pixel bandwidth, 4 views-per-segment, a temporal resolution of 55.28ms (TE_{IN}) and 34.08ms (TE_{MIN}), 20 phases reconstructed from a 24 second acquisition using retrospective ECG gating and an artificial ECG signal (1000ms; 60bpm), and through-plane velocity encoding with a VENC of 150cm/s. Eddy current-induced velocity offsets were measured at the exact locations corresponding to the ascending aorta (aAo), main pulmonary artery (PA), and right and left pulmonary arteries (RPA/LPA) used to measure blood flow in N=10 healthy subjects. Data were collected using both the HBW+TE_{IN} and LBW+TE_{MIN} protocols. The eddy current induced velocity offsets for each protocol were averaged in space and time to yield a single eddy current induced velocity offset for each patient and each flow territory. The data were non-Gaussian distributed and of unequal variance, therefore bootstrap statistical comparisons were used for the eddy current induced velocity offset data by randomly resampling 1000x with replacement. The 95% confidence intervals (95%-CIs) of the medians for TE_{IN} and TE_{MIN} were compared for each flow territory.

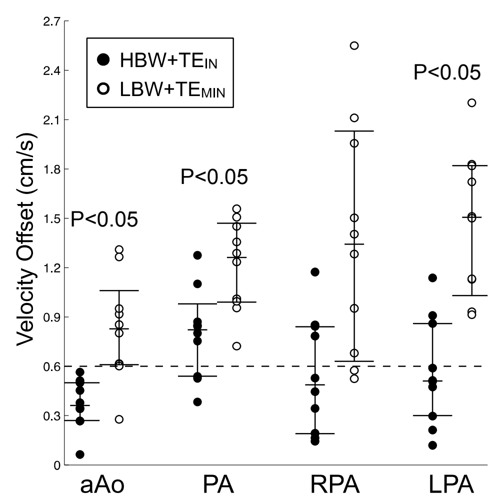

Figure 2. Eddy current induced velocity offsets at HBW+TE_{IN} are reduced compared to LBW+TE_{MIN} for measurements in the aorta (aAo), pulmonary artery (PA), and right and left pulmonary arteries (RPA/LPA). The dashed line represents an acceptable (*9*) offset of 0.6cm/s.

RESULTS – The medians and bootstrapped 95%-CIs of the medians show that eddy current induced velocity offsets are statistically lower (no overlap of the 95%-CIs) for HBW+TE_{IN} compared to LBW+TE_{MIN} in the aAo, PA, and LPA (P<0.05, Fig. 2). Additionally, the median eddy current-induced velocity offsets are less than the 0.6cm/s threshold of acceptable eddy current-induced velocity offsets (*9*) at HBW+TE_{IN} for the aAo, RPA, and LPA, whereas the medians and lower-bound 95%-CIs for LBW+TE_{MIN} exceed 0.6cm/s for all territories.

DISCUSSION – Eddy current-induced velocity offsets in PC-MRI measurements are reduced in the chemical shift optimized PC-MRI protocol (HBW+TE_{IN}) compared to the default clinical protocol (LBW+TE_{MIN}) used at our institution for measurements made in the aAo, PA, and RPA/LPA. Therefore, the use of HBW+TE_{IN} improves the accuracy and robustness of PC-MRI, compared to LBW+TE_{MIN}, by reducing two significant sources of error – chemical shift and eddy currents.

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