Flow-Induced Phase Effects in Non-Subtractive Fat-Water Separated MRA

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TARGET AUDIENCE: Physicists and clinicians interested in contrast-enhanced MR angiography (MRA) and chemical-shift fat-water separation

PURPOSE: Chemical-shift-based fat-water separation using a 2-point Dixon method was recently used for non-subtractive contrast-enhanced MR angiography (CE-MRA) in the lower extremities [1,2]. Suppressing the bright signal from subcutaneous fat and bone marrows using a Dixon-based method obviates the need for a pre-contrast mask subtraction, leading to a higher signal-to-noise ratio (SNR) and a lower sensitivity to motion. However, with multi-echo acquisitions, bipolar readout gradients are often used to acquire the signal at multiple echo times following application of a single radiofrequency (RF) excitation. The bipolar readout acquisition increases the sampling efficiency compared to acquiring echoes with different echo times in different TRs, but it creates a number of phase errors, some of which are addressed during the image reconstruction process [3,4]. Furthermore, bipolar readout gradients create an extra phase shift for spins flowing in the readout direction. As ***Figure 1*** shows, a typical readout gradient has different first moment (M1) values at the time of the first and second echoes. In the presence of flow, the signal equation from a pixel containing water (W) and fat (F) at each echo time can be written as:

$$S(TE_n) = \left(We^{iM1_nV} + Fe^{i2\pi\Delta f TE_n}\right)e^{i2\pi f_B TE_n}$$

where V is the velocity of flowing spins in the readout direction, Δf is the fat-water chemical shift (434 Hz at 3.0 T between water and the main methylene peak) and f_B is the sum of the background phase variations. Blood flow is highly pulsatile and variant in the lower extremities through the cardiac cycle but CE-MRA methods are not normally gated. The theoretical flow-induced phase shift between the first and second echo signal can be calculated as:

$$\Delta\varphi = \left(\mathrm{M1}(TE_2) - M1(TE_1)\right)V$$

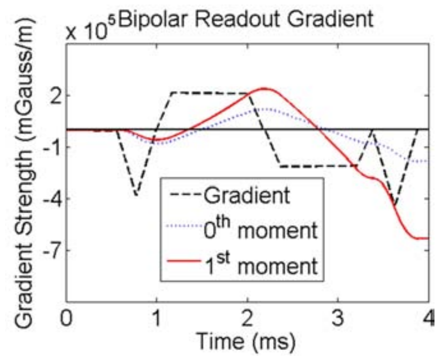

FIG1. Different first moment (M1) values at TE_1 and TE_2 create a phase shift in flowing spins that is unaccounted for in the fat-water separation signal model.

The purpose of this work was to investigate the effects of flow-induced phase shifts in 2-point Dixon fat-water separation as it is relevant to applications in non-subtractive MRA of the lower extremities using a controlled flow phantom.

METHODS: <u>*Phantom Design:*</u> A stenosis phantom (diameter = 12 mm narrowed to 2.5 mm at the location of stenosis) filled with a gadolinium-doped water mixture was used with a mast-roller flow pump (Stöckert, Sorin Group, Milan, Italy) to produce flow rates of 0 to 1.0 L/min at every 0.1 L/min interval and flow rates of 1.0 L/min to 2.5 L/min at every 0.5 L/min interval. These flow rates simulate a range of physiologically-relevant velocities from 0 to 37 cm/s through the thicker portion of the tube and 0 to 178 cm/s through the stenosis.

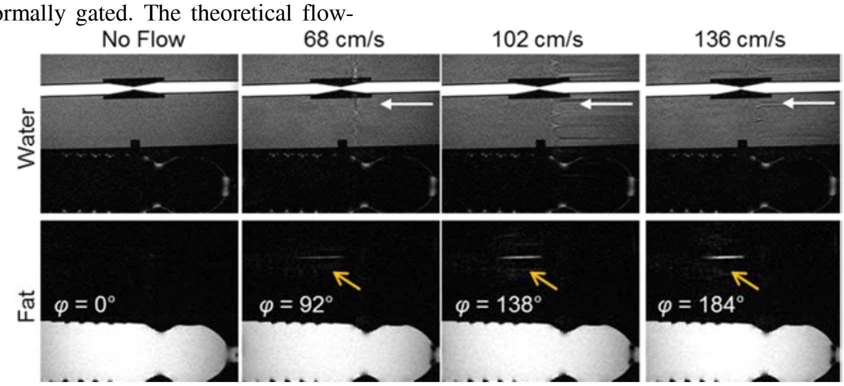

FIG2. Extra phase shifts accumulated by moving spins can interfere with the Dixon fat-water separation algorithm. Signal from water rapidly flowing (in the directions shown by the white arrow) through a stenosis can appear in the fat image (orange arrows). Top row numbers show the estimated average flow velocity at the narrowest part of the stenosis. φ shows the estimated flow-induced phase shift.

<u>*Pulse Sequence:*</u> Scanning was performed on a 3T MRI system (Discovery MR750, GE Healthcare, Waukesha, WI) using an 8-channel cardiac array coil. A dual-echo spoiled gradient-recalled pulse sequence was used. Imaging parameters included: coronal excitation, FOV = 44 cm (S/I) × 40 cm (R/L) × 16 cm (A/P), true isotropic spatial resolution of 1.4 mm × 1.4 mm × 1.4 mm, flip angle=12°, bandwidth = ±166.7 kHz, TR/TE_1/TE_2 = 4.0/1.1/2.2 ms, and R = 2 × 2 data-driven parallel imaging. At each flow rate evaluated, image acquisition was repeated using the same scan parameters but collecting signals from each of the two echoes in a separate TR = 3.9 ms (non-bipolar readout gradients) to eliminate the phase effects from the bipolar readout gradients. The velocities of the flowing spins were estimated using conservation of mass and ignoring turbulent flow effects.

RESULTS: ***Figure 2*** shows water and fat images after processing with the Dixon algorithm. Flowing spins accumulate an extra phase shift when bipolar readout gradients are used and are wrongly mapped into the fat image at higher flow rates, causing an overestimation of the degree of stenosis in the water image. ***Figure 3*** shows water, fat, out-of-phase (TE_1), and in-phase (TE_2) images acquired with the pump set at a flow rate of 0.5 L/min (corresponding to 35 cm/s maximum velocity) using bipolar (both TEs in the same TR) and non-bipolar (each TE in a separate TR) readout gradients. The scan time for the method that used non-bipolar readout gradients (two TRs) was nearly twice as long as the method that used bipolar readout gradients (single TR).

DISCUSSION: Bipolar readout gradients induce flow-related phase shifts that require particular attention when fat-water separated methods are used for MRA. Flow effects can be mitigated by avoiding bipolar readout gradients and acquiring each echo in a separate TR, which results in increased scan time. Flow effects can also be reduced if the readout gradients are specifically designed to minimize the difference between M1 at TE_1 and TE_2.

CONCLUSION: The effects of flow-induced phase shifts for fat-water-separated imaging of stenosis are demonstrated using a controlled phantom study. Bipolar readout gradients can create unwanted fat-water swaps in areas of high flow. Swaps can be avoided by using non-bipolar readouts.

REFERENCES: [1] Michaely et al. Invest. Radiol. 2008;43(9):635-641. [2] Leiner et al. Euro. Radiol. 2013;23(8):2228-2235. [3] Yu et al. JMRI 2010;31(5):1264-1271. [4] Ma et al. MRM 2008;60(5):1250–1255.

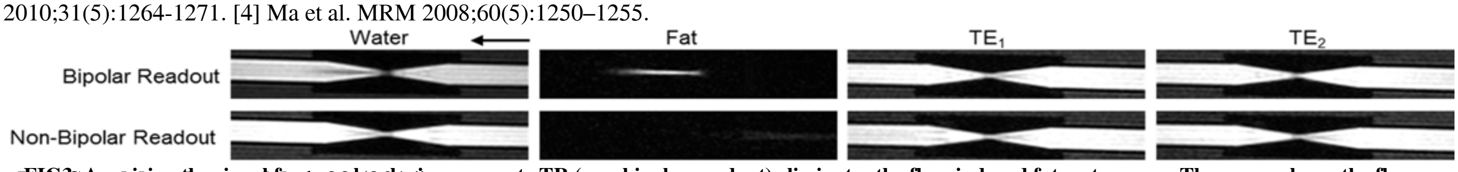

FIG3. Acquiring the signal from each echo in a separate TR (non-bipolar readout) eliminates the flow-induced fat-water swap. The arrow shows the flow direction.