Chemical Shift Induced Phase Errors in Phase Contrast MRI

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INTRODUCTION – Phase contrast MRI (PC-MRI) is subject to numerous sources of error (eddy currents (1), Maxwell terms (2), gradient field distortions (3), chemical shift (4,5)), which decrease both quantitative accuracy and clinical confidence in the reported measures. These errors frequently lead to disagreement between the net forward flow (mL) in the ascending aorta (aAo), main pulmonary artery (PA), and the sum of the right/left branch pulmonary arteries (RPA+LPA), which in the absence of shunts should be equal. Established correction methods exist for many of these errors, but ***the effects of chemical shift in PC-MRI have not been thoroughly evaluated***. The ***objectives*** of this study were to:

1) Quantify the contribution of chemically shifted perivascular fat to PC-MRI flow measurement errors.
2) Demonstrate that a judicious choice of bandwidth (BW) and TE can reduce chemical shift induced phase errors in PC-MRI net forward flow measurements in the aAo, PA and RPA+LPA to clinically insignificant levels.

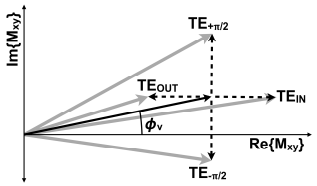

Figure 1. Effect of chemical shift (ϕ_{CS}, angle between the black and any gray lines) on the measured phase (ϕ_V) at different TEs. Dashed lines demonstrate the LBW effect and would be shorter at HBW. This effect does not subtract in phase difference processing

THEORY – Perivascular fat surrounds most vessels and can chemically shift across the vessel wall into the lumen, thereby superposing the off-resonant phase and magnitude of the fat signal onto the complex signal in a pixel containing flowing blood. This phase error is not eliminated in phase difference processing and can lead to a clinically significant over- or underestimation of blood velocity. The spatial shift of fat, and thus the percent of partial-volumed fat within a pixel, is greater at low BW (LBW) compared to high BW (HBW). The chemically shifted fat signal superposes with the blood pixels near the vessel wall, which are typically slow flowing and therefore have near-zero velocity phase. Thus, if the phase of fat is close to the phase of stationary water, (TE_{IN}, Fig. 1) then the chemical shift error will be smaller than when the phase of fat deviates more from that of blood ($TE_{\pm\pi/2}$, Fig. 1). Collectively, the chemical shift induced phase errors (angle between the black and gray lines in Fig. 1) at different BWs and TEs can be summarized by Eq. [1] for the parameters we tested. Therein *Truth* is defined by the absence of chemical shift errors:

$$LBW{+}TE_{IN} < HBW{+}TE_{IN} \sim Truth < HBW{+}TE_{+\pi/2} < LBW{+}TE_{+\pi/2} \qquad [1]$$

METHODS – The theory of chemically shifted perivascular fat in PC-MRI (*4*) was extended through the acquisition of blood flow measurements made in the aAo, PA, RPA, and LPA of ten (N=10) volunteers (3 female, 7 male; age 25.9±4.7 years) with no previous history of cardiovascular disease. High-resolution black blood turbo spin echo (TSE) images were also acquired with and without fat saturation (Fat-Sat) to define the presence (or absence) of perivascular fat. The PC-MRI imaging protocol used a 3T scanner (Siemens Trio) and cine spoiled gradient echo velocity-encoding sequence: constant 8.5ms TR, 4.92/5.54ms TEs ($TE_{IN}/TE_{+\pi/2}$), 192×120 matrix, 1.7mm×1.7mm×6mm voxels, 30° flip angle, LBW=401Hz/pixel and HBW=814Hz/pixel, 4 views-per-segment, a temporal resolution of 68ms, 20 phases reconstructed from a 20 second acquisition using retrospective ECG gating, GRAPPA (*6*) parallel imaging (~2x acceleration and 24 reference lines), and through-plane velocity encoding with a VENC of 150cm/s. All datasets were eddy current corrected using a stationary phantom (*1,7*).

RESULTS – Figure 2 illustrates the effects of chemical shift on net forward flow measurements in the aAo and PA at $LBW{+}TE_{IN}$, $HBW{+}TE_{IN}$, $HBW{+}TE_{+\pi/2}$, and $LBW{+}TE_{+\pi/2}$ for ten subjects. Changing the BW and TE consistently leads to systematic changes in the measured flow according to Eqn. 1. The maximum difference (Δ_{Max}) in the measured net forward flow is presented above each dataset. In the presence of perivascular fat the bar-charts step upward from $LBW{-}TE_{IN}$ (smaller Δ_{Max}) to $LBW{-}TE_{+\pi/2}$ (larger Δ_{Max}) as expected in Eqn. [1]. For vessels in which minimal perivascular fat (Fig. 3) was observed (* below each dataset) the trend is much flatter (low Δ_{Max}) compared to vessels with perivascular fat. Subjects with perivascular fat had significantly larger Δ_{Max} compared to subjects without perivascular fat in all vessel territories: aAo (6.4±2.8 vs. 1.8±0.5, p=0.01), PA (11.9±5.8 vs. 2.0±0.9, p=0.04), LPA (4.3±1.0 vs. 1.3±1.0, p=0.003). All of the RPA vessels had visible perivascular fat. The mean intrasubject flow difference and variance between vessel territories was significantly smaller for $HBW{+}TE_{IN}$ compared to $LBW{+}TE_{+\pi/2}$ in all paired vessel comparisons (Table 1).

DISCUSSION – Chemically shifted perivascular fat leads to a previously unappreciated clinically and statistically significant over- or underestimation of quantitative PC-MRI flow measurements. This effect is largely governed by the TE and BW, for a given spatial resolution, field strength, and vessel wall thickness. Our *in vivo* results indicate that poor selection of the BW and TE can lead to a large error in PC-MRI net forward flow measurements when perivascular fat is present (e.g. 11.9±5.8mL in the PA). Chemically shifted perivascular fat induced phase errors are minimized by the use of $HBW{+}TE_{IN}$, which significantly improves intrasubject net forward flow agreement as indicated by decreased intrasubject flow differences across the aAo, PA, and RPA+LPA (Table 1). The increased signal available at 3T offsets any apparent signal decreasing owing to the use of a $TE_{IN}>TE_{MIN}$ and HBW. Note that $TE_{MIN}\sim TE_{-\pi/2}$ on our systems. Minimization of chemical shift errors in other flow territories where perivascular fat is present (e.g. renals, heart, carotids, etc.) will likely be clinically important. This work quantified the contribution of chemically shifted perivascular fat in through-plane PC-MRI measurements. The same analysis could be conducted for in-plane velocity measurements, which are slower compared to through-plane velocities and may be affected more by chemical shift.

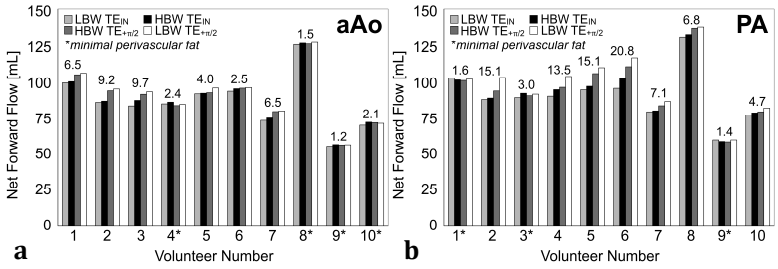

Figure 2. Net forward flow (mL) data from the aAo **(a)** and PA **(b)**. The maximum difference (Δ_{Max}) in the measured net forward flow is presented above each dataset. (*) indicates that minimal perivascular fat was observed. $HBW{+}TE_{IN}$ minimizes chemical shift induced flow measurement errors.

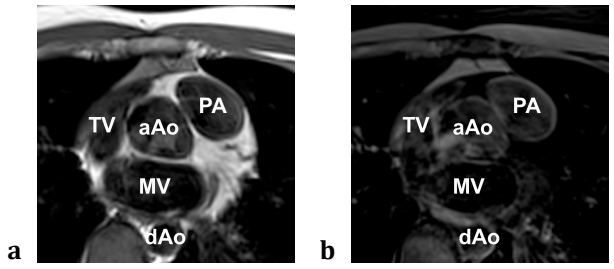

Figure 3. TSE **(a)** and TSE with Fat-Sat images **(b)** highlight the presence of perivascular fat, especially around the PA. TV-tricuspid valve; MV-mitral valve; and dAo-descending aorta.

Table 1. Mean intrasubject flow difference (mL)			
	$HBW{+}TE_{IN}$	**$LBW{+}TE_{+\pi/2}$**	**P-Value**
aAo vs. PA	4.9 ± 2.4	9.8 ± 6.4	0.01
aAo vs. RPA+LPA	1.3 ± 0.8	4.0 ± 3.2	0.03
PA vs. RPA+LPA	2.0 ± 0.3	5.0 ± 2.9	0.03

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