# THE EFFECTS OF CHEMICALLY SHIFTED PERIVASCULAR FAT IN QUANTITATIVE PHASE CONTRAST MRI

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**Introduction:** Phase Contrast MRI (PC-MRI) is a routine clinical noninvasive imaging technique used to measure the velocity of blood with flexible spatial and temporal resolution [1,2]. Despite recent advances, improvements in PC-MRI accuracy are still needed. Phase measurements in MRI are subject to quantitative inaccuracy due to eddy currents [3], gradient field distortions [4], Maxwell terms [5] and chemical shift [6]. Perivascular fat can chemically shift across the vessel wall and into the lumen, thereby leading to over or underestimation of blood velocity within a vessel. The ***objective*** of this study was to describe the effect of the readout bandwidth (BW) and echo time (TE) on chemically shifted perivascular fat in quantitative PC-MRI using computer simulations, flow phantom data and *in vivo* studies.

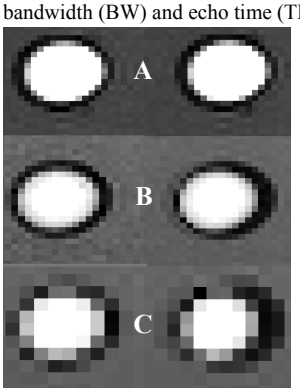


**Fig. 1.** Fat chemically shifts to the right, less so at high **(left column)** compared to low **(right column)** BWs for different protocols (**A.** No fat, **B.** Fat at our clinical protocol, **C.** Fat at low resolution).

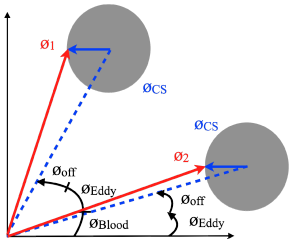


**Fig. 2.** Chemical shift in PC-MRI. BW scales the radius of the gray circle (magnitude of the chemical shift contribution) while the TE determines the phase.

**Methods:** *Imaging*–All measurements were performed on a 3 Tesla system using a 16-channel coil array and retrospective ECG gating. Data was collected in the superficial femoral artery of three healthy consenting volunteers. The protocol used a cine spoiled gradient echo PC-MRI sequence (256x160 matrix, 30° flip angle, 1.3mm$^2$ x 6mm resolution, 4.94 or 5.39ms TE, 8.58 or 9.48ms TR, BWs of 222 and 888 Hz/pixel, 3 $k_y$-lines per segment and temporal resolutions of 51.5 or 56.9 ms. Through-plane velocity encoding was performed using interleaved flow-compensated and flow-sensitive encoding with a VENC of 75cm/s. Phantom measurements were using the above protocol with a 4-channel head coil, a VENC of 20cm/s and 6.03/9.67 TE/TR obtained in a superficial femoral artery phantom containing a sealed tube (19.1/1.6mm outer diameter/wall thickness) surrounded by either water or vegetable oil (fat). Blood-mimicking fluid (40% glycerol) was circulated through the phantom by a computer-controlled pump, which generated a constant flow of 18mL/s. SNR differences, which arised from using different BWs, were compensated with averaging. The datasets were eddy current corrected. Net flow profiles were processed offline. *Computer Simulations*–Parabolic blood flow exhibiting a tri-phasic waveform was simulated to match the physical vessel characteristics of the *in-vivo* studies. The fat and blood magnitudes were determined analytically based on their velocities [7] while the fat phase was determined from the TE and frequency difference between fat and water. Perivascular fat was chemically shifted in accordance with the spatial resolution and BW. The net phase was calculated on a pixel-by-pixel basis by Eq. 1, where M is the signal magnitude for the subscripted tissues, phi is the phase of blood/eddy currents, Δf is the fat/water frequency difference, and TE is the echo time:

$$\phi = \arg\left(M_{blood}e^{i(\phi_{blood}+\phi_{eddy})} + M_{fat}e^{i2\pi\Delta fTE}\right) - \arg\left(M_{blood}e^{i\phi_{eddy}} + M_{fat}e^{i2\pi\Delta fTE}\right) \quad (1)$$

Pixels containing blood and chemically shifted fat produced a net phase that deviated from measured blood (undesired), whereas regions unaffected by fat had a net phase resulting only from flowing blood (desired). Ideally the theoretical, experimental, and *in vivo* would be consistent, thereby validating the simulation and the mathematical basis for the effects of chemical shift for *in vivo* quantitative PC-MRI.

**Results:** The chemical shift effect in PC-MRI can be seen within the magnitude images from the phantom studies in Fig. 1. Fig. 1A is devoid of fat surrounding the phantom vessel, whereas Figs. 1B and 1C contain surrounding fat. The spatial shift of perivascular fat can be clearly seen in our clinical protocol (Fig. 1B) and even more so at an exaggerated low-resolution protocol (Fig. 1C). In addition to the magnitude PC-MRI images, theory demonstrates that chemical shift does not equally affect the flow-compensated and flow-sensitive experiments (Eq. 1 and Fig. 2). Therefore, ***chemical shift effects do not cancel during phase difference processing and lead to over or underestimation of blood velocities***. Excellent agreement between experimental and simulation results illustrates that chemical shift disrupts (over or underestimation based on the BW and TE) quantitative PC-MRI measurements and that these effects can be reduced by increasing the BW (Figs 3-5). The velocities of the pixels near the vessel wall, assuming the no-slip boundary condition, are near zero. The use of an in-phase TE leads to a slight decrease in measured phase (the phase of blood is near zero and the phase of fat acts to slightly reduce the net phase, Fig. 3: blue dotted line). Conversely, the use of an out-of-phase TE leads to an increase in net phase (the phase of blood is near zero while the phase of fat acts to slightly increase the net phase, Fig. 3: blue dashed line). The use of a mid-phase TE leads to a larger increase in the net phase if the fat phase is oriented along pi/2 (Fig. 3: black dashed line) and a decrease in net phase if the fat phase is oriented along –pi/2 (Fig. 3: black dotted line). In-phase TE *in vivo* results (Fig. 4) and mid-phase TE (pi/2) *in vivo* results (Fig. 5) are comparable to theoretical results (Fig. 3). Differences between Figs. 3 and 4 are addressed in the discussion section. Similar results were seen for the other *in vivo* datasets.

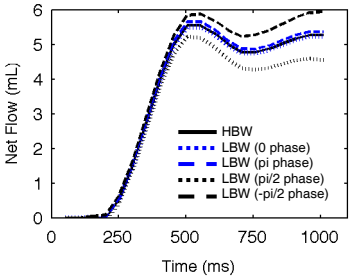


**Fig. 3.** Simulation results showing the role of TE on chemical shift induced artifacts for net flow.

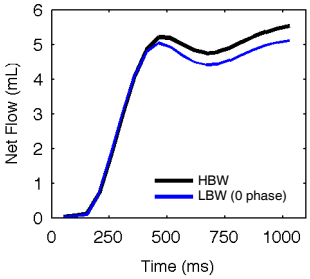


**Fig. 4.** *In vivo* results (in-phase TE). The use of a low bandwidth leads to an underestimation in net flow of 0.41 mL (7.7 %).

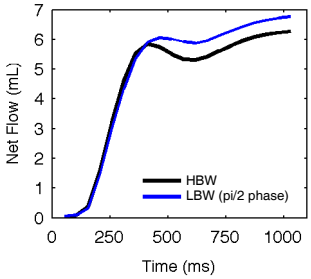


**Fig. 5.** *In vivo* results (pi/2 phase TE). The use of a low bandwidth leads to an overestimation in net flow of 0.49 mL (7.5 %).

**Discussion:** The overestimation of net flow at low BW *in vivo* (Fig. 4) compared to theoretical results (Fig. 3) can be attributed the observed flow profile *in vivo*, which was not parabolic. Pixels near the vessel wall exhibited velocities that were not near zero, thus leading to a further increase in the net phase due to the out-of-phase TE. The effects are mitigated by using high BW, which requires less scan time due to a reduction in the available TE/TR, but there is a concomitant decrease in SNR. Another method for eliminating the shift of perivascular fat into the vessel is to increase the spatial resolution, but this comes at the expense of increased scan duration and breath-hold times, which can be problematic for thoracic and abdominal vessel imaging. The spatial resolution/wall thickness used in this study was comparable to current clinical protocols. Fat/water separated imaging techniques or fat saturation pulses can eliminate the chemical shift effects of fat at the cost of additional scan time or measurements. The femoral artery was chosen for *in vivo* studies to increase the reproducibility of the analysis between multiple scans and to obviate the need for respiratory gating.

**Conclusions:** The BW controls the magnitude of the spatial shift of perivascular fat into the vessel and affects the accuracy of quantitative blood flow measurements. High BWs reduce, or eliminate (depending on vessel characteristics and imaging resolution), the spatial shift of perivascular fat into the vessel and increase the accuracy of quantitative blood flow measurements. The TE controls the direction in which fat corrupts PC-MRI measurements. For parabolic laminar flow, mid TEs (pi/2 and -pi/2) are most detrimental to quantitative PC-MRI measurements as they are oriented perpendicular to the phase of slow flowing blood near the vessel wall.

**References:** 1. N.J. Pelc, *Magn Reson Imaging Clin N Am* **3**, 1995. 2. J. Lotz, *Radiographics* **22**, 2002. 3. A. Chernobelsky, *J Cardiovasc Magn Reson* **9**, 2007. 4. M. Markl, *Magn Reson Med* **50**, 2003. 5. M.A. Bernstein, *Magn Reson Med* **39**, 1988. 6. M.A. Bernstein, *J Magn Reson Imaging* **1**, 1991. 7. J.H. Gao, *Med Phys* **15**, 1988.