Multi-Slice Breathhold Phase-Sensitive Coronary Vessel Wall Imaging at 3T

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Introduction
Black-blood coronary vessel wall imaging is a powerful non-invasive tool for the quantitative assessment of positive arterial remodeling. Although dual-inversion-recovery (DIR) is the standard current for non-invasive coronary vessel wall imaging, optimal lumen-vessel wall contrast is sometimes difficult to obtain and the time-window available for imaging is limited due to the competing requirements between T1 (blood signal nulling time), TD (period of minimal myocardial motion), and heart rate. In addition, atherosclerosis is a spatially heterogeneous disease and therefore imaging at multiple anatomical levels of the coronary circulation is mandatory. However, both enhanced volumetric coverage and black-blood contrast typically come at the expense of increased scanning time. Phase-sensitive IR⁴⁵ (PS-IR) has shown to be a valuable tool for enhancing tissue-tissue contrast and for making IR imaging less sensitive to T1. This work extends PS-IR to PS-DIR, and combined with spiral-imaging, multi-slice black-blood coronary vessel wall imaging is enabled in a single breath-hold.

Methods
Theory: After a DIR pre-pulse (Fig. 1), the inversion time T1 = T1* in [0.5(1 + exp(−TR/T1))] allows for signal-nulling of the in-flowing blood at the anatomical level of interest. The highest blood-tissue contrast in the magnitude image is obtained when an image is acquired at TI = T1*. Although the MR signal is complex (magnitude and phase), DIR images only show the magnitude of the signal with a suboptimal blood-tissue contrast if TI<T1*. However, by additionally exploiting the MR signal phase, a signed (+/-) black-blood image can be acquired at TI-T1* and reconstructed with a blood-tissue contrast that is higher than that obtained at TI*. Simultaneously, competing constraints related to TI* and TD are avoided. The removal of these constraints thus enables multi-slice black-blood coronary vessel wall imaging in a single breath-hold at no extra cost in scanning time or acquisition window duration per slice.

Reconstruction: The 2D complex DIR image intensity Ĉ(x,y) can be approximated by Ĉ(x,y) ≈ M(x,y)P(x,y) − M(x,y)S(x,y)eiπ(2x/y), where M(x,y) and P(x,y) are the modulus, magnitude and the phase of the image. The function S(x,y) is a binary sigmoid function such that S(x,y) = (2x/y+1) in the tissue or re-inverted blood, and S(x,y) = (2x/y−1) in the inverted blood. ε(x,y) is the quadrupole phase errors. To estimate ε(x,y) in and around the vessel, a local region-growing reconstruction algorithm was developed. Pixels with high signal in close proximity to the cross-sectional coronary artery are selected as seed points. The phase values of these points are then used to estimate the local signal phase inhomogeneity, which is needed for local signed-magnitude image reconstruction. Once ε(x,y) is estimated, a signed image i(x,y) can be reconstructed from the acquired data using

i(x,y) = M(x,y)P(x,y) − M(x,y)S(x,y)eiπ(2x/y) + ε(x,y).

Implementation: A single breathhold multi-slice DIR sequence was implemented (Fig. 1) on a clinical 3T Philips-Achieva MRI system. Data were acquired using a segmented k-space spiral acquisition with spectral spatial excitation. Image processing was performed off-line on a personal computer using Matlab.

Experiments: A flow-phantom was built using a plastic tube with 6 mm lumen-diameter and 3 mm wall-thickness, and with continuous tap-water flowing at an average speed of 20 cm/s. The tube was embedded in agarose gel. Phantom images were acquired a TI of 75, 125, 175, 225, and 275ms. In vivo images were acquired with anatomical slices perpendicular to the proximal part of the right coronary artery (RCA) around end-systole and image localization was similar to a previously published methodology. To demonstrate the gain in CNR, single-slice single-phase PS-DIR images were acquired with incremental TI ranging from 50ms-400ms in 15 healthy adult subjects (slice thickness=8mm, FOV=190x190 mm, matrix=320x320, interleaves=20, acquisition window=18 ms / interleaf, breath-hold duration= 22 sec). Further, dual-continuous-slice single-phase PS-DIR images with the same imaging parameters were acquired in 4 healthy adult subjects. Blood-vessel wall CNR was then calculated on both the DIR and PS-DIR in vivo images.

Results
Phantom magnitude and phase data are shown in Fig. 2 together with reconstructed PS-DIR signed images. Note the abruptly changing signal in the region of the tube on the phase images in the first three slices (dashed arrows). Using conventional DIR, an maximum water-agarose contrast was obtained for the fourth slice only (dotted arrow) in which water signal was almost null. In contrast to this and with the PS-DIR method, a high water-agarose contrast was obtained not only in one, but in four of the consecutively acquired slices in which the signal inside the tube was inverted (solid arrows). Using TI<T1* in the in vivo experiments, Fig. 3 shows that PS-DIR enables delineation of the coronary artery vessel wall in both acquired slices (solid arrows) and supports an increased wall-lumen contrast when compared to conventional DIR (dashed arrows) in which TI was too short for adequate signal-nulling of the blood-pool signal. Consistent with these visual in vivo findings, Fig. 4 shows that the CNR was significantly higher (p<0.05, paired t-test) in PS-DIR over a broad range of TI. The arrow in Fig. 4 is located at T1* where optimized contrast for DIR is obtained.

Discussion
PS-DIR provides a TI-insensitive higher-CNR alternative to conventional DIR for coronary vessel wall imaging. TI-insensitivity can be traded for enhanced volumetric coverage at no extra-cost in imaging time. While slow flowing blood has not been a limitation within the TI range utilized in this study, this range remains to be further investigated in patients with lumen-narrowing disease.

References