High-Resolution T1- And T2-Weighted Black Blood Inner Volume 3D Fast Spin Echo Imaging For Characterizing Vessel Wall Components In Vivo

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Introduction: Given the increasing prevalence of peripheral artery disease (PAD) [1], noninvasive MRI techniques for accurate vessel wall thickness measurements have enormous potential to impact peripheral vein bypass graft (PVBG) patient management given that early PVBG failure often manifests as wall thickening. Furthermore, the small wall thickness of PVBGs and the opportunities they present for studying the pathophysiology of bypass graft arterialization render them an excellent vascular bed for the development and testing of novel vessel wall MR imaging methods. In this work, application of a high spatial resolution, cardiac gated, black blood, high sampling efficiency, inner volume 3D FSE sequence [2] to the study of lower extremity PVBGs in 14 subjects demonstrated a significant difference in vessel wall area between T1- and T2-contrast weightings. The median vessel wall difference of 5.45 mm^2 that was found between contrast weightings not only highlights the immediate need for novel ultra-high resolution MRI methods, but also has ramifications for semi- and fully-automated vessel wall component characterization and atherosclerotic plaque detection [3].

Methods: Experiments were performed on a GE 1.5T Excite MR scanner (GE Medical Systems, Milwaukee, WI) using the body coil for RF transmission and a 5" circular surface coil for reception. Fourteen non-reversed saphenous vein PVBG patients (10 male, mean age 65.6 +/- 11.5 years, 3 patients at 1 month post-implantation, 6 patients at 6 months, 5 patients at 12 months) were imaged with a inner volume 3D FSE (IV3DFSE) sequence [2] that uses two different echo spacings. The first echo is generated by magnetization only within the intersection of two large time-bandwidth highly selective radiofrequency (RF) excitations applied orthogonal to each other (inner volume), while subsequent echoes are generated using tightly packed 0.5 ms-long non-selective refocusing RF pulses [4] and using measures to ensure that only magnetization contributing to the first echo contributes to subsequent echoes [2]. Inner volume selection reduces total imaging time, while non-selective refocusing RF pulses reduce echo train duration and maximize FSE sampling efficiency. For each patient IV3DFSE cardiac gated DIR black-blood protocols optimized for T1W and T2W imaging [5] were used to image a 3 x 3 x 3.6 cm volume with 96 x 96 x 18 matrix (frequency x phase x slice, 312 mm x 312 mm x 2 mm voxels), with slice encoding aligned with the PVBG. T1W images were acquired with 12 ETL, 16 kHz BW, 16 ms TE and 1 R-R TR. T2W images were acquired with 18 ETL, 10 kHz BW, 60 ms TE and 2 R-R TR. T2W scans additionally used fat-resonance selective saturation. Imaging time was 9.5 min per contrast at 60 bpm. For each subject, free-hand vessel wall area (VWA) measurements were made by outlining the inner and outer vessel wall borders for each contrast over 10 to 18 contiguous slices, depending on slice SNR imitations due to receiver coil placement, and subtracting the inner area from the outer area. The exact Wilcoxon signed rank test was used to compare the median difference and ratio between the T1 and T2 VWAs. In addition, graft lumen area measurements (inner wall areas) were also correlated with "gold-standard" gray scale ultrasound sonography (US), which was obtained prior to MR imaging at 3 locations (1cm spacing) within the volume imaged by IV3DFSE. In order to explain the difference in VWA between T1W and T2W images, the signal curve was obtained at 16 time points (TEs ranging from 17 to 230 ms) for two excised specimens, immersed in saline shortly after excision, using a multi-echo version of the IV3DFSE [6] augmented with stimulated and indirect echo suppression [7]. T_2 relaxation time constants for mono- and bi-exponential models were fitted to the signal decays of individual voxels selected from the two vessel wall layers that were visible in late echo images (an outer dark layer was visible due to the bright surrounding saline). For one of the specimens, vessel wall composition was obtained with Masson's trichrome stain histology.

Results: High quality images were obtained in all 14 patients, allowing free-hand VWA measurement. Examples from two patients are shown in Figs. 1 & 2. There was no significant difference between US and MR lumen measurements (P=0.18), reflecting minimal MR blood suppression artifact. The range of the vessel wall areas was 12-24 mm^2 for T1W images and 7-15 mm^2 for T2W images. The graft wall area measured from T1W images was significantly larger than that measured from T2W images (P<0.001); the median difference in VWA was 5.45 mm^2 (95% CI: 3.86, 6.92 mm^2). The median of the ratio of T1W versus T2W VWA over all subjects was 1.52 (95% CI: 1.38, 1.72). For all subjects, a significant increase of the outer vessel wall accounted for the larger vessel wall area of the T1W images. In both excised specimens, signal in ROIs placed in the dark outer layer visible in late echo images (Fig. 3) appeared to decay bi-exponentially (P<0.00001): for the first specimen (Fig. 3), T_2 values in that layer were 27 ms for 73% of content, and 103 ms for the remainder, while for the second specimen (not shown) they were 38.5 ms for 46% content, and 118.6 ms for the remainder. For reference, mono-exponential T_2 fits to these ROIs were 53 ms and 52.9 ms respectively. Signal in ROIs in the inner bright layer appeared mono-exponential (P=.686), with T_2 values of 231.5 ms and 257.7 ms for the first and second specimens respectively. Note that unlike the apparently healthy specimen in Fig. 3, the other specimen had nearly complete lumen loss due to myointimal hyperplasia. Correlative histology in the second specimen suggested that the brighter layer consisted of myofibroblast cell type embedded in a proteoglycan-rich matrix while the outer darker layer was consistent with relatively fewer cells within a dense collagen fibrous tissue.

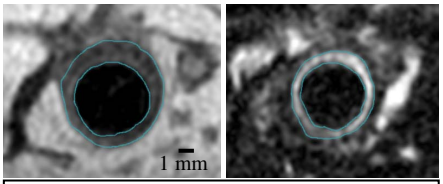

Figure 1 T1W (left-hand) and T2W (right-hand) images obtained from a 60 yr old PVBG patient, demonstrating the larger free-hand wall area (outer boundary area minus inner boundary areas) on T1W image in comparison to T2W image.

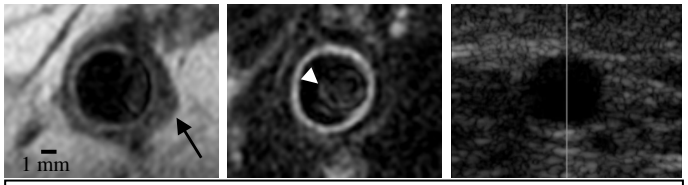

Figure 2 T1W (left), T2W (middle) and US (right) images in 58 yr old PVBG patient at 1 month post-implantation demonstrating outward expansion of the wall in T1W image (black arrow). Some slow flow artifact is demonstrated in the T2W image (white arrowhead) but it does not obscure visualization of the vessel wall.

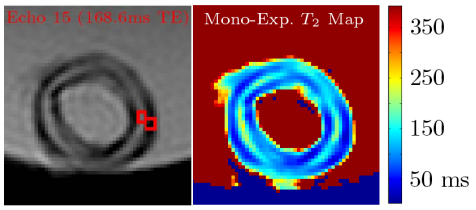

Figure 3 Left: Image of excised PVBG specimen at 15th of 16 echoes (168.8 ms TE), showing two single voxel ROIs (0.195 mm^3 voxel volume), one in each layer of the vessel wall. Right: Map of mono-exponential decay time constants fitted to the observed signal decay curves.

Conclusion: An efficient inner volume 3D FSE approach to vessel wall imaging provides very high spatial resolution suitable for accurate lumen and wall area characterization. In lower extremity peripheral vein bypass grafts imaged within the first year after surgery, vessel wall areas measured from T1W images are significantly larger than those measured from T2W images. The difference is attributed to highly different T_2 values in the two distinct layers that compose the vessel wall, both of which are visually apparent in the high-resolution MR images. These are tentatively attributed to the media and adventitia of the vessel wall, based on histological verification of one specimen. Very high spatial resolution vessel wall T1W and T2W MR imaging can thus not only be performed in clinically viable times, but can also enable accurate differentiation and area and volume measurement of vessel wall components.

Grant Sponsors: Whitaker Foundation, NIH K23-EB00882, R01-HL075771. **References:** [1] Sumner et al, Circulation 2007;116:II_780. [2] Mitsouras et al, Med Phys. 2006;33:173-86. [3] Liu et al, MRM 2006;55:659-68. [4] Mugler et al, Radiology 2000;216:891-9. [5] Mitsouras et al, ISMRM 2007;p.2472. [6] Mitsouras et al, ISMRM 2006;p.3026 [7] Poon et al, JMRI 1992;2:533-40.