Ultra-High Resolution Vessel Imaging at 1.5T: Peripheral Vein Bypass Graft Wall Imaging via Non-Selective Refocusing Inner Volume 3D Fast Spin Echo

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Introduction: The challenges of high resolution vascular MRI include pulsation in the R-R cycle and blood flow. Scan time is also important, and should ideally be less than 10 minutes. In peripheral venous bypass graft (PVBG) patients, MR techniques such as accurate wall thickness measurement and true-T2 analyses of the PVBG have enormous potential to impact patient management and to offer a window into the pathophysiology of bypass graft arterialization. PVBG failure, characterized by wall thickening, can occur within two years and is typically attributed to proliferation of intimal hyperplasia at the anastomoses, or prior valve sites within the graft. Correction of early failure is essential for limb salvage, rendering non-invasive graft surveillance critical. The typical graft wall thickness (300-400 μm), in conjunction with the limited acquisition time available during the relatively quiescent portion of the R-R cycle (~200 ms), render many MRI methods inappropriate. For example, to achieve 300 μm spatial resolution with 4 G/cm-15 G/cm/ms gradients, phase encoding and rephasing alone requires at least 3 ms, dramatically limiting the number of echoes that can be acquired in the acquisition window. At present, vessel wall T1- and T2-weighted imaging is performed at 390μm x 390μm x 4mm resolution using 2D FSE [1]. In this project, 5 patients underwent *in vivo* PVBG black-blood imaging at true resolution of 312μm x 312μm x 2mm using an inner volume 3D FSE (IV3DFSE) sequence that employs two separate echo spacings through the echo train [1]. The first echo occurs at an extended echo time, but contains signal only from within the intersection of two high-quality slab-selective excitations applied orthogonal to each other. Subsequent echoes are closely spaced, formed by non-selective (0.5 ms) refocusing RF pulses, with measures to ensure that only magnetization contributing to the first echo contributes to subsequent echoes. The reduced FOV optimizes total imaging time, while the minimized echo train duration optimizes FSE dephasing-induced blurring. The latter can be traded for increased resolution and/or SNR without affecting imaging time.

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. Five PVBG patients were imaged with both the product cardiac 2D FSE on our system, and the IV3DFSE. T1W and T2W contrast was obtained with each sequence. All scans used DIR blood nulling, and T2W scans additionally used fat-resonance selective saturation. 2D imaging was performed over five 4mm-thick slices with 6mm gap, and 10 cm FOV with 256x256 matrix (0.61 mm^3 voxels). Imaging time was 10.5 min at 60 bpm with 4 NEX. T1 weighting was obtained with 14 ms TE, 1 R-R TR, 32 kHz BW and 8 ETL. T2 weighting was obtained with 58 ms TE, 2 R-R TR, 16 kHz BW and 16 ETL. IV3DFSE imaging was performed over 18 2mm-thick slices and 4 NEX, requiring 9.5 min imaging time at 60 bpm. The imaged FOV was 3 cm, and a 96x96 matrix was used (0.195 mm^3 voxels). For T2W imaging a 0.75 phase FOV (2.25 cm, 72 matrix) was used. T1 weighting was obtained with 16 ms TE, 1 R-R TR, 16 kHz BW and 12 ETL. T2 weighting was obtained with 58 ms TE, 2 R-R TR, 10 kHz BW and 18 ETL. Total readout duration (acquisition window) was similar for respective protocols; the reduced echo spacing afforded by the IV3DFSE sequence was traded for (a) reduced BW to increase SNR, (b) longer ETL to reduce total imaging time, and (c) the longer phase encode gradients required for the increased resolution. Resolution and SNR were analyzed for each protocol; true in-plane resolutions were determined from the point-spread functions (PSF) resulting from the respective echo train timing [3] and an approximation of the T2 decay of signal emanating from the PVBG wall. To obtain the T2 decay rate approximation, true-T2s were measured for an *in vitro* PVBG imaged in saline 6 hours after excision, using a 3D multi-echo sequence (32 echoes) with stimulated and indirect echo crushing and composite (90_x-180_y-90_x) refocusing pulses [4]. Through-plane resolution was determined by Bloch simulation of the RF pulses for the 2D sequence, and the standard phase encoding Fourier PSF for the 3D sequence. SNR measurements for each protocol were obtained from a doped water phantom imaged at the same conditions as the *in vivo* experiments.

Results and Discussion: The table summarizes prescribed and achieved resolutions for each protocol, and SNRs expected (based on interaction of voxel volume and acquisition time), and measured. As indicated, IV3DFSE did not sacrifice signal dephasing or SNR, despite the reduced imaging time and significantly enhanced (by 3-fold) voxel resolution. The multi-echo experiment revealed bi-exponential behavior in ROIs covering the vessel wall, with a 99.23-99.995% probability (reduced χ^2=0.47 and 0.27, at an SNR of ~86 at 1st echo). Figure 1 shows the probability that each voxel imaged with the multi-echo sequence exhibited bi-exponential decay, as well as maps showing the percentage of each voxel's content observed to exhibit decay rates of 10-60 ms, and 60-350 ms. The distribution of actual decay rates in each map and normal distribution fits of the distributions are also shown. The mean and standard deviations of these fits (marked on the x axis of the plots) afford increased confidence in the decay rates used for resolution analysis. Selected 2D & 3D images from one case are shown in Fig. 2. Curved planes through the A/P center of the PVBG were also extracted from the 3D cubes, as shown in Fig. 2. Reformatting was not useful for the 2D scans. The smooth variation of the vessel wall apparent in the reformatted views allows increased confidence in thickness measurements obtained from the source slices. The proposed method presents significant potential to enhance achievable resolution at 3T, and to manage imaging time particularly in conjunction with parallel imaging.

	T1W 2DFSE	T1W IV3DFSE	T2W 2DFSE	T2W IV3DFSE
Prescribed Phase encode Resolution	391 μm	312.5 μm	391 μm	312.5 μm
Phase encode FWHM (% increase)	511 μm (131%)	423 μm (135%)	540 μm (138%)	419 μm (134%)
Prescribed Slice Width	4 mm	2 mm	4 mm	2 mm
Slice Width @10% Max (% incr.)	7.3 mm (183%)	3.7 mm (185%)	7.3 mm (183%)	3.7 mm (185%)
Relative Theoretical SNR	1	1.17	1	0.9
Measured SNR (% of 2DFSE)	34.97	40.98 (117%)	38.4	32.42 (84%)

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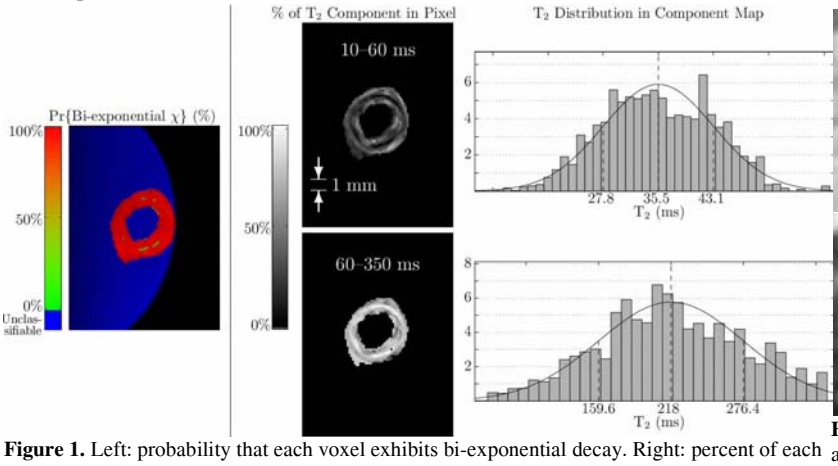

Figure 1. Left: probability that each voxel exhibits bi-exponential decay. Right: percent of each voxel within a fixed T2 range, and % distribution within that range.

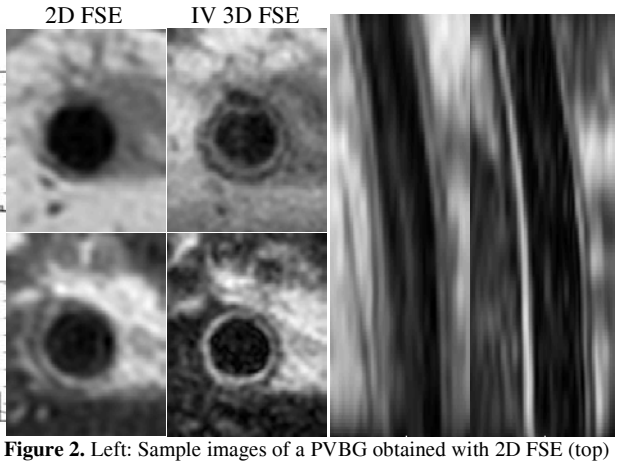

Figure 2. Left: Sample images of a PVBG obtained with 2D FSE (top) and IV3DFSE (bottom). Right: IV3DFSE curved plane reformats through the A/P center of the graft.

References: [1] Mitsouras et al. Med Phys. 2006;33:173-86. [2] Fayad et al. Circulation. 2000;102:506-10. [3] Mulkern et al. Med Phys. 1991;18:1032-37. [4] Mitsouras et al. Proc. 14th ISMRM. 2006;p3026.