Simulation and Phantom Study of Wall Shear Stress in Arteriovenous Grafts

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TARGET AUDIENCE: Nephrologists, cardiologists, cardiovascular physiologists, scientists, and engineers with interests in phase-contrast MRI.

PURPOSE: Arteriovenous Grafts (AVGs) are the preferred access method for many dialysis patients, particularly those whose vessels do not allow for the placement of the more common AV fistula. Unfortunately, despite the large number of people who rely on AVGs for their dialysis, AVGs are prone to stenotic buildup that frequently leads to thrombosis and graft failure [1]. Generally, the most significant stenosis around AVGs occurs on the inner vein wall just downstream from the graft-vein anastomosis [2]. It has been proposed that this spot may be particularly prone to stenosis as a result of low wall shear stress (WSS) in this region arising from both the geometry of the graft-vein junction and the asymmetrical flow patterns (pressure, velocity, etc.) of the vein and the adjoining graft inlet [3]. We hypothesize that low WSS does in fact occur in the region of interest under conditions resembling those of an AVG-vein anastomosis.

METHODS: First, a computational fluid dynamics (CFD) analysis was performed. The Y-shaped geometry of two 12.7-mm-diameter tubes intersecting at a 45° angle (Fig. 1) was constructed using Ansys Fluent software (Ansys, Inc. Canonsburg, PA). Several different ratios of graft to vein flow rates were applied to the geometry to study the graft-vein anastomosis. It was important that turbulent flow be accounted for in this analysis, so a *k-ε* turbulence model was used as the basis for all flow calculations. The software did not allow for the use of a turbulent flow model along with a non-Newtonian fluid model, so the non-Newtonian properties of blood were ignored for this analysis and water was used as an approximation. Next, a flow phantom was constructed and imaged using phase-contrast MRI to obtain velocity data, from which WSS could be computed. The phantom, as pictured on the left side of Fig. 2, consisted of a large outer loop of 12.7-mm-diameter tubing filled with water with a shunt pathway connecting the two sides of the loop together and joining the main loop at a 45° angle. A small clamp was placed in the outer loop to mimic the resistance of a capillary network in the body, creating a significantly lower flow rate in the further branch of the main loop than in the shunt segment. This unequal division of flow, along with the geometry of the model, gave an approximation of the situation in an actual AVG, where higher-pressure blood shunted from the artery through the AVG flows at an angle into the much lower-pressure vein. The phantom used simple steady-state flow (not periodic) of approximately 400 mL/min. The phantom was imaged in a Siemens 3 Tesla MRI scanner (Siemens Healthcare, Germany) with a 3D cine phase contrast sequence using a simulated ECG trigger. A single 4 mm thick slice was acquired with FOV 210 X 280 mm, 336 X 448 matrix, TR/TE = 100.3/5.5 ms, VENC = 20cm/s, 3 views per phase. 6 phases were acquired with a temporal resolution of 116.7 ms, but only the first image was analyzed.

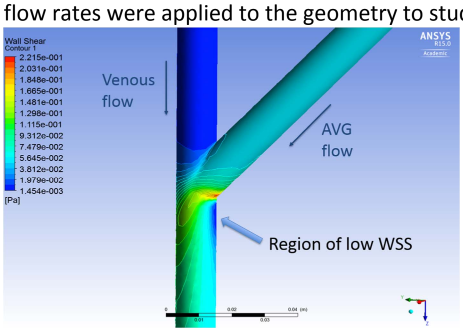

Fig. 1: Wall shear stress (WSS) computed from a CFD simulation of a AVG – vein anastomosis with graft-to-vein flow ratio of 80:20.

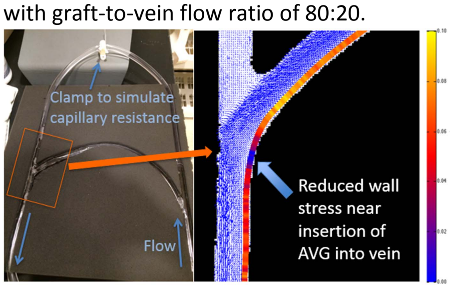

Fig. 2: *Left*: AVG flow phantom. *Right*: In-plane velocities (blue vectors) measured by phase-contrast MRI and wall shear stress (colored region)

RESULTS: Fig. 1 shows a result of CFD analysis. A distinct region of low WSS is present on the inner wall of the vein (straight section), just downstream from the point representing the graft-vein anastomosis. For flow ratios ranging from 50:50 to 95:5, a low-WSS region was present in this same spot in each case. Table 1 lists wall stresses in this region and at a point 3.0 cm downstream for a range of graft to vein flow rates. For the first several entries, the table shows an increasingly lower WSS values near the anastomosis with increasing graft to vein flow rates. As the flow ratio increases, the anastomosis WSS increases the low-WSS region becomes more spread out, but the pattern of low WSS near the anastomosis is maintained. In-plane phase contrast velocities and wall stress measured in the loop phantom are shown in Fig. 2, where it can be seen that a distinct region of low WSS is present in the Y-shaped phantom on the inner wall of the vein (straight section), just downstream from the point representing the graft-vein anastomosis. The graft to vein flow rate in the phantom was ~80:20 and the wall stresses near the junction and 3.0 cm downstream were 0.01 and 0.87 dynes/cm^2 respectively, which are close to the values in Table 1.

Table 1. Wall shear stress (WSS) in dynes/cm^2 from CFD Simulations Using Various Ratios of Graft Flow Rate to Vein Flow Rate

	Graft:Vein Flow Ratio					
	50:50	*60:40*	*70:30*	*80:20*	*90:10*	*95:5*
Near graft-vein anastomosis	0.12	0.07	0.03	0.01	0.04	0.04
~3 cm downstream	0.52	0.49	0.49	0.50	0.50	0.49

DISCUSSION: Given a flow geometry resembling that of an AVG vein-graft anastomosis, both CFD simulations and MRI scans of a practical flow model indicated the presence of a substantial pocket of low WSS at the spot predicted by the hypothesis. A limitation of this study is that neither of the approaches utilized took into consideration periodic flow within the AVG or the unique non-Newtonian properties of blood.

CONCLUSIONS: Phase contrast MRI can be used to measure wall stress near AVG vein-graft anastomosis and can potentially be used to predict and prevent graft failure due to thrombosis.

REFERENCES:[1] Beathard et al Adv Ren Replace Ther 1994; [2] Kanterman et al Radiology 1995; [3] Fitts et al Open Urol Nephrol J 2014.