SB3C2015
Summer Biomechanics, Bioengineering and BIotransport Conference
June 17-20, 2015,Snowbird Resort, Utah, USA
SB³C2015-442

BETTER ASSESSMENT OF ARTERIOVENOUS FISTULA PATENCY USING FUNCTIONAL DIAGNOSTIC ENDPOINTS

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INTRODUCTION

Arteriovenous fistula (AVF) is the widely recommended method of vascular access (VA) for hemodialysis; however, failure of AVFs due to stenosis is one of the major concerns in the dialysis population [1]. A significant stenosis (> 75% area reduction) results in considerable reduction in venous flow rate (< 500 ml/min) and ultimately, failure of the VA for supporting dialysis. Therefore, early diagnosis of stenosis can provide an opportunity to intervene in a timely manner to either assist the maturation process or avoid thrombosis. Currently, venous flow rate (Q_a) and the ratio of venous pressure to arterial pressure (VAPR) are used to detect stenosis in AVFs [2]. A Q_a < 500 ml/min and a VAPR > 0.55 are considered as signs of a significant stenosis. However, Q_a has only shown to be a good predictor of an inflow stenosis (a constriction at anastomosis area) in AVFs [2]. The Q_a can diagnose a significant outflow stenosis (a constriction at the outflow tract of the vein) only at the late stages when the stenosis has adversely affected the hemodynamics or resulted in thrombosis. AVFs can maintain a high Q_a at initial stage of an outflow stenosis due to formation of collateral pathways, causing diagnostics complexities. Alternatively, VAPR was developed to detect outflow stenosis in grafts but, it has shown to be a poor predictor of stenosis in AVFs.

The major criticism of the current diagnostic endpoints is that they are either based on flow or pressure, while both of these parameters change in the presence of a stenosis. We have recently showed in a pig model [2] that pressure drop coefficient (C_p: ratio of pressure drop to dynamic pressure at proximal artery) and resistance index (R: ratio of pressure drop to velocity at proximal artery) can distinguish between the adverse and favorable changes in hemodynamics and thus, can better diagnose stenosis in AVFs. Here, our *primary objective* is to assess the variation of C_p and R with changes in flow rate and stenosis severity in an idealized baseline model, developed from realistic geometries of AVF. This will allow evaluation of the efficacy of these parameters for the accurate diagnosis of stenosis.

METHODS

Geometry. The 3D geometry of the AVF and its corresponding schematic are shown in Figures 1A and 1B, respectively. The baseline geometry of the AVF was adopted from the average geometrical features of the AVFs that were created in porcine model [2]. The arterial segment of the AVF consisted of the proximal and distal arteries, while venous segment was comprised of anastomosis, S-shaped, and outflow regions. The diameters of the proximal and distal arteries and

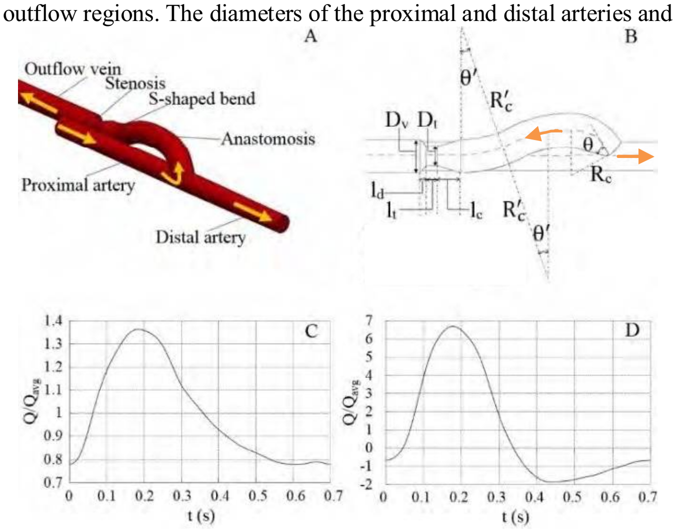

Figure 1. (A) AVF geometry, (B) schematic of AVF, normalized flow rate pulses at (C) proximal artery and (D) distal artery

the vein were 8.2, 7.0, and 9.4 mm, respectively. The anastomotic angle (θ) was 67°, while the radius of curvature (R_c) of anastomosis was 12 mm. The radius of curvature (R_c') and the subtended angle (θ') for the successive bends of the S-shaped region were 29.9 mm and 28.7°, respectively. The stenosis was located at the end of the S-shaped region. Since there was not much information available on the stenosis profile in AVFs, the stenosis geometry was considered to be axisymmetric with trapezoidal profile, representing the shape of idealized stenotic plaques [3]. The lengths of the converging (l_c), throat (l_t) and diverging (l_d) sections were 6.0, 3.0, and 1.5 mm for all cases, respectively. D_v and D_t (Figure 1B) are the diameters of the vein and stenosis throat, respectively. The analysis was conducted for four cases with percentage area stenosis (%AS = $\{D_v^2 - D_t^2\}/D_v^2$): 0%, 65%, 75%, and 85%. D_t were 5.6, 4.7, and 3.7 mm for geometries with 65%, 75% and, 85% AS, respectively.

Numerical Analysis. The AVF geometry was meshed using prism elements near the wall and tetrahedral elements at the core. In the numerical analysis, the vessel walls were assumed to be rigid and the blood flow was considered to be unsteady, non-Newtonian, incompressible and laminar. The analysis was performed using Fluent (version 14.5, ANSYS Inc.). The pulsatile velocity pulses were applied to the proximal artery inlet and distal artery outlet, whereas a stress free boundary condition was applied at the vein outlet. The flow rate (Q) pulses [4] at proximal and distal arteries normalized by the corresponding average Q are shown in Figures 1C and 1D, respectively. For the present study, three different average Q were considered at the proximal artery including 600, 1000, and 1600 ml/min, while the average Q at the distal artery had a constant level of 108 ml/min for all cases. These values were based on our flow measurements for AVFs in the porcine model [2].

Functional Diagnostic Endpoints. Resistance index (R) and pressure drop coefficient (C_p) were defined as follows:

$$R = \Delta p/v \qquad (1)$$

$$C_p = \Delta p/(0.5\rho v^2) \qquad (2)$$

where Δp is the time-averaged pressure drop between the proximal artery inlet and vein outlet over one cardiac cycle, v is the time-averaged velocity at the proximal artery inlet, and ρ is the blood density (= 1050 kg/m³). The R was obtained by linearly scaling the pressure drop with flow (velocity at the proximal artery), while in C_p, the Δp was normalized non-linearly with velocity (square of velocity at proximal artery).

RESULTS

Variations of Δp, R, and C_p with respect to %AS for the three different flow rates (Q) are shown in Figures 2, 3A, and 3B, respectively. Also, for more clarity, the corresponding values of Δp, R, and C_p at different %AS and Q are reported in Tables 1, 2, and 3, respectively. The Δp, R and C_p are elevated with the increase in stenosis severity (%AS) for all Q values. Also, for any %AS, the Δp and R increased with the rise in Q. However, for all %AS severities, increase

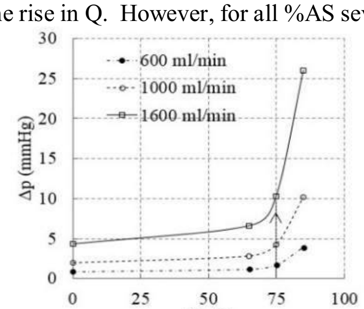

Figure 2. Variation of Δp with %AS for three different Q

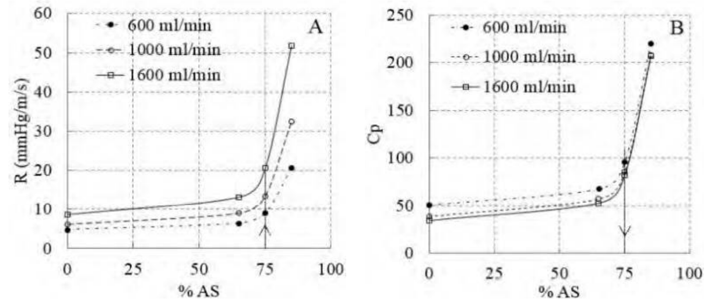

Figure 3. Variation of (A) R and, (B) C_p with %AS for three different flow rates.

in Q resulted in the decrease in C_p values. For instance, for a 75% AS as the Q decreased from 1600 ml/min to 600 ml/min, the R reduced from 20.5 to 9 mmHg/m/s, while C_p increased from 81.9 to 96.2. Here, the reduction in Q represents adverse hemodynamic condition in the AVF caused by the stenosis. Therefore, any increase in C_p can be either associated with the elevation of %AS or the decrease in Q or a combination of the two in AVFs. Thus, C_p can better diagnose the stenosis severity and its corresponding adverse effects on hemodynamics of AVFs as compared to R.

Table 1. Variation of Δp with respect to %AS for three different Q

		Δp (mmHg)			
	%AS	0	65	75	85
Q (ml/min)	600	0.9	1.2	1.7	3.9
	1000	1.9	2.8	4.2	10.2
	1600	4.3	6.6	10.3	26

Table 2. Variation of R with respect to %AS for three different Q

		R (mmHg/m/s)			
	%AS	0	65	75	85
Q (ml/min)	600	4.8	6.4	9	20.7
	1000	6.1	8.9	13.4	32.5
	1600	8.6	13.2	20.5	51.9

Table 3. Variation of C_p with respect to %AS for three different Q

		C_p			
	%AS	0	65	75	85
Q (ml/min)	600	50.9	67.9	96.2	220.7
	1000	38.7	57	85.5	207.7
	1600	34.2	52.5	81.9	206.8

DISCUSSION

Both C_p and R increased with rise in %AS, which was consistent with the findings of our recent study on porcine model [2]. In this study we determined that at all levels of %AS, R decreased with the reduction in Q, while C_p increased. The former can be explained by the fact that any reduction in Q is associated with a more pronounced decrease in Δp. The decrease in R due to reduction in Q can be considered as one of the shortcomings of this parameter as a diagnostic endpoint. However, due to non-linear relation of velocity (square term in denominator) with C_p, the index C_p has a higher resolving power for detecting the adverse effects of stenosis on the hemodynamics of AVFs. Therefore, *C_p can better distinguish the reduction in Q due to formation of stenosis as compared to R, and thus, can be used as a diagnostic endpoint to assess the functionality and patency of AVFs.*

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