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ANALYSIS OF THE PRESSURE FIELD IN RIGID ARTERIOVENOUS FISTULA WITH VARIATION IN THE AREA OF THE ANASTOMOSIS

Alexsandra Tomé dos Santos

Willyam Brito de Almeida Santos

Federal University of Rio Grande do Norte, Department of Mechanical Engineering, Center of Technology, Laboratory of Fluid Mechanics, Avenue Senador Salgado Filho, 300 – Lagoa Nova, CEP 59078-970 – Natal/RN

alexandra__santos@hotmail.com

willyambas@gmail.com

Everton Guedes de Lima

everton.gl@hotmail.com

Jonhattan Ferreira Rangel

ferreira.rangel.095@ufrn.edu.br

Kleiber Lima de Bessa

klbessa@ct.ufrn.br

Abstract. In recent years, the number of patients with chronic renal failure (CRF) has increased. For the treatment of these patients, hemodialysis is performed. Arteriovenous fistula (AVF) is an access that provides continuous and long-term treatment, however, failure in maturation of the AVF and thrombosis in mature fistulas has been the main cause of morbidity and mortality in hemodialysis patients. This work aims to analyze the pressure field in a rigid wall arteriovenous fistula with variation in the anastomotic area, trying to establish a relationship between pathological regions and pressure values. From the computational modeling and 3D printing, three AVFs were made with variation in the anastomotic area, the anastomosis width (W) was fixed at 4 mm while the anastomosis length value (L) was varied by 5 mm, 6 mm and 7 mm, resulting in a cross-sectional area (AST) of 15.7 mm², 18.8 mm² and 22.0 mm² respectively. From the results obtained, it was observed that the variation in the size of the anastomosis considerably influences the pressures upstream of the anastomosis, with greater energy dissipation the shorter the anastomosis length.

Keywords: FAV, Anastomotic width, Anastomotic length, Energy dissipation, Pressure drop

1. INTRODUCTION

Chronic Renal Failure (CRF) is a disease with a strong socioeconomic impact on the health care of patients treated by the public and/or private health system in Brazil. According to the Brazilian dialysis census 2018, carried out by the Brazilian Society of Nephrology (BSN), it is estimated that approximately 134.000 patients with CRF are treated by dialysis methods and, of these, 92.2% by hemodialysis (Neves et al., 2020).

Arteriovenous Fistula (AVF) is a surgical technique that allows the connection between an artery and a vein. Thus, an AVF acts as a low-resistance, high-compliance pathway between the high-pressure arterial system and the low-pressure venous system (Sivanesan et al., 1998). Many articles suggest the AVF as the best Vascular Access (VA) for patients hemodialysis treatment, as it is a durable access and has low complication rates (Krzanowski et al., 2011; Briones et al., 2010; Akoh, 2009; Dixon, 2006).

The construction of AVF generated conditions that contribute to increase blood flow through the venous system. However, as geometric changes associated with increased flow result in variation in the pressure field, and consequently, disturbances in blood flow with the generation of recirculating zones, stagnation points and non-physiological condition of shear stress levels on the wall of the vessel. Thus, hemodynamic conditions induce vascular remodeling mechanisms, which contribute to the onset and development of endothelial dysfunction (Stolic, 2013). Studies shown that 20 to 60% of AVF have primary failure (December 2011; Huijbregts et al., 2008; Allon et al., 2002). However, once AV maturation was achieved, FAV required less interventions than other types of AV to maintain long-term permeability for dialysis (Allon, 2007).

In recent years, many studies have been carried out in order to assess the causes that can lead to AVF failure. Van Canneyt et al. (2010) published the first study evaluating the hemodynamic impact of anastomosis size and angle on pressure drop and flow distribution, numerical simulation was performed adopting rigid vessel walls, nonpulsatile and laminar flow. According to Van Canneyt et al. (2010), evaluating the effects of modifiable VA surgery settings, such as

the size and Angle of the Anastomosis (AA), can reduce the failure rate and contribute to the success of AVF maturation, however a change in 2 mm in the length of the anastomosis can increase the pressure drop by more than 30%.

In order to contribute to the analysis of the flow behavior in an AVF, this work aims to better understand the effects of hemodynamics in the AVF with variation in the anastomotic area in vitro models.

2. METHODOLOGY

2.1 FAV Modeling

The drawings were performed using Fusion 360 software (Autodesk). The AVF were ideally designed adopting the radiocephalic dimension, with a diameter of 4 mm in the artery and 6 mm in diameter in the venous segment (Hassan et al., 2012). The connection between the radial artery and the cephalic vein was made through an anastomosis, assuming an ellipsoidal cross section, with Anastomotic Width (W) and Length (L), as shown in Figure 1.

In this work, 3 (three) FAVs were manufactured with the AA fixed at 45° , L fixed at 4 mm and W being 5 mm, 6 mm, and 7 mm, final cross-sectional area (AST) of 15.7 mm^2 , 18.8 mm^2 and 22.0 mm^2 respectively.

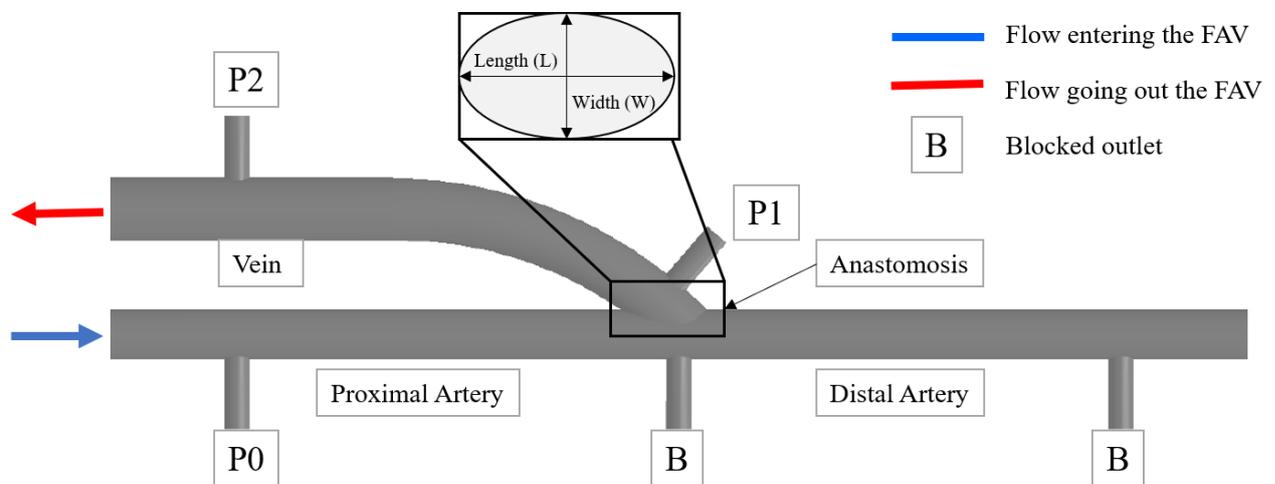


Figure 1. Front view of the idealized radiocephalic arteriovenous fistula.

Pressure taps were inserted perpendicular to the segments. The distal artery was considered occluded, since pressure in the radial artery at the anastomosis may be higher than, equal to, or less than pressure in the distal radial artery (Kheda et al., 2009)

2.2 FAV Manufacturing

The fistulas were printed using 3D printing using the Fused Deposition Modeling (FDM) technique. The AVF was manufactured by filament extrusion by thermoplastic material of Acrylonitrile Butadiene Styrene (ABS) in a Da Vinci 1.0 Pro model printer. To ensure the structural strength of the AVF, it was built in successive layers with 100 % fill and 2 mm offset thickness based on internal volume.

2.3 Experimental Bench

The experimental bench used in the experiment was developed at the Laboratory of Fluid Mechanics - LFM of the Federal University of Rio Grande do Norte (UFRN), which was configured to generate steady flow, promoting the flow of fluid through the vessels under analysis, capturing the pressure and flow data at certain points of the system, as shown in Figure 2.

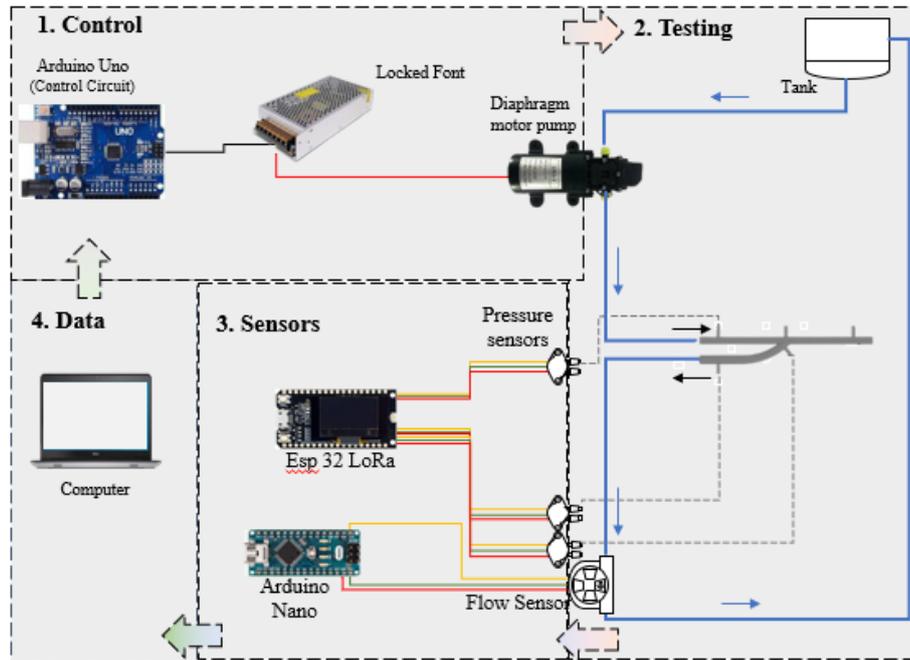


Figure 2. Schematic drawing of the experimental bench

To simulate the flow in the radiocephalic AVF with the distal artery occluded, the connections were placed in the proximal artery and in the vein. Pressure data were collected at pressure measurements P0, P1 and P2, and the flow was collected in the vein segment. Pressure data were captured by pressure transducers model MPX5050DP and flow data by flow sensors model USN-HS41TA.

The experiment in steady state was controlled through the engine load ranging from 30 to 80 %, with a 5 % load increase, due the engine restrictions and AVF configuration.

2.4 Data Treatment

During the experimental procedure, it collected a series of data for each increase in engine load, in order to reduce the instability of the system components. For each engine load, he selected a range of 100 (one hundred) data and applied the average of the values. The graphs were generated from the average values of pressure and flow at each engine load.

3. RESULTS AND DISCUSSION

Pressure data were synchronized with steady-state flow rate data on AVF for anastomosis with sizes L5mm x W4mm, L6mm x W4mm and L7mm x W4mm, as shown below. It is noteworthy that the pressure and flow range was limited by the geometry of the AVF and the load applied to the motor.

In Figure 3, three graphs are presented containing the pressure data obtained as a function of the flow in each fistula, being in (a) for AVF with L5mm, (b) with 6Lmm, and (c) with L7mm.

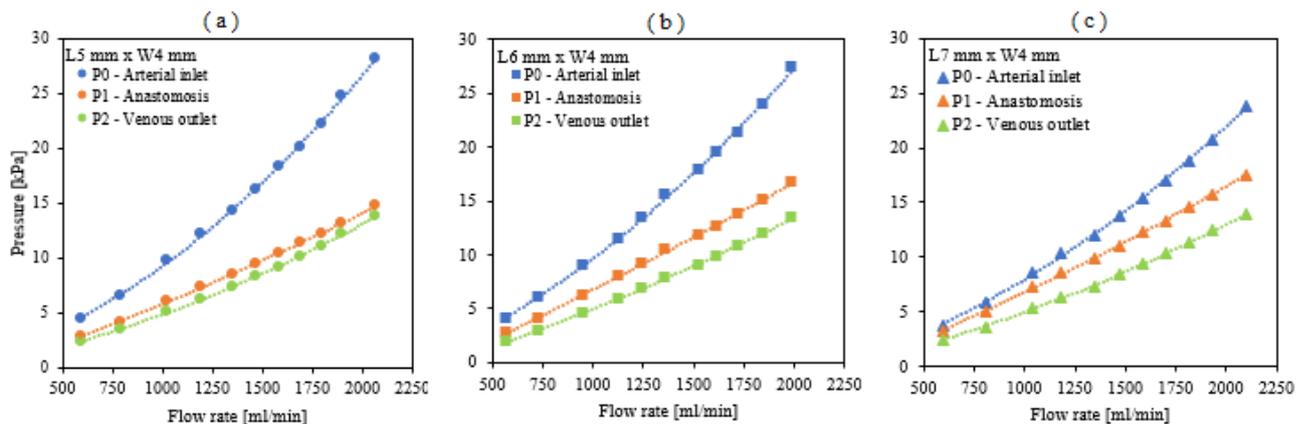


Figure 3. Pressure by flow graph.

In Figure 3a, it can be seen P0 with a pressure of 4,49 kPa (33,68 mmHg) at a flow rate of 588,98 mL/min, increasing to a pressure of 28,31 kPa (212,34 mmHg) for a flow rate of 2066,55 mL/min. At P1 the pressure of 2,83 kPa (21,23 mmHg) for a flow of 588,98 mL/min, increasing to a pressure of 14,78 kPa (110,86 mmHg) for a flow of 2066,55 mL/min. In P2 the pressure of 2,41 kPa (18,08 mmHg) for a flow of 588,98 mL/min, increasing to a pressure of 13,86 kPa (103,96 mmHg) for a flow of 2066,55 mL/min.

In Figure 3b, it can be seen P0 with a pressure of 4,13 kPa (30,98 mmHg) at a flow rate of 588,98 mL/min, increasing up to a pressure of 27,42 kPa (205,67 mmHg) for a flow rate of 2066,55 mL/min. At P1 the pressure of 2,72 kPa (20,40 mmHg) for a flow of 588,98 mL/min, increasing to a pressure of 16,78 kPa (125,86 mmHg) for a flow of 2066,55 mL/min. In P2 the pressure of 1,96 kPa (14,70 mmHg) for a flow of 588,98 mL/min, increasing to a pressure of 13,46 kPa (100,96 mmHg) for a flow of 2066,55 mL/min.

In Figure 3c, it is possible to observe P0 with a pressure of 3,80 kPa (28,50 mmHg) at a flow rate of 588,98 mL/min, increasing to a pressure of 23,74 kPa (178,06 mmHg) for a flow rate of 2066,55 mL/min. At P1 the pressure of 3,34 kPa (25,05 mmHg) for a flow of 588,98 mL/min, increasing to a pressure of 17,57 kPa (131,79 mmHg) for a flow of 2066,55 mL/min. In P2 the pressure of 2,47 kPa (18,53 mmHg) for a flow of 588,98 mL/min, increasing to a pressure of 13,92 kPa (104,41 mmHg) for a flow of 2066,55 mL/min.

It can be noticed an increasing of pressure in both outlets as a function of the increase in flow. The AVF with an anastomosis length of 5 mm showed the greatest change in system pressure, since the pressure drop between the arterial inlet and the anastomosis was 7,01 kPa (52,58 mmHg) and between the anastomosis and the venous outlet was only 1,00 kPa (7,50 mmHg). By increasing the length of the anastomosis from 5 mm to 6 mm, there is a reduction in the pressure drop between the arterial inlet and the anastomosis to 5,36 kPa (40,20 mmHg), whereas between the anastomosis and the venous outlet the pressure drop is 2,32 kPa (17,40 mmHg). In the fistula with an anastomosis length of 7 mm, there is an equalization of the pressure drop in both segments, with a pressure drop between the arterial inlet and the anastomosis of 2,88 kPa (21,60 mmHg), and between the anastomosis and the venous segment of 2,50 kPa (18,75 mmHg). Thus, this behavior demonstrates that the pressures downstream of the anastomosis are more sensitive to shorter anastomotic lengths.

In Figure 4, the pressure variation data anastomosis are presented with the length of 5 mm, 6 mm and 7 mm at the P0 pressure taking during the experiment in the AVF.

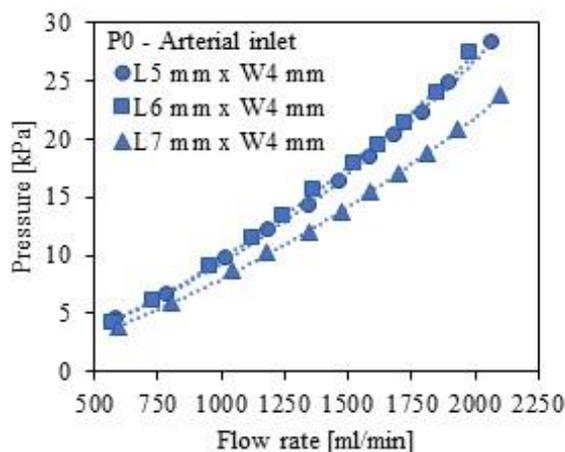


Figure 4. Arterial inlet pressure graph by flow rate

It can be noticed an increasing of the pressure as a function of the increase in flow. It is observed that the variation in arterial inlet pressure between fistulas with anastomotic lengths of 5 mm and 6 mm is small, with a pressure of 4,49 kPa (33,68 mmHg) and 4,13 kPa (30,98 mmHg) increasing to 28,31 kPa (212,34 mmHg) and 27,42 kPa (205,67 mmHg), respectively, varying on average to 0,72 kPa (5,40 mmHg). However, fistula with anastomosis length of 7 mm had lower pressure when compared to fistula L5mm and L6mm, with pressure of 3,80 kPa (28,50 mmHg) increasing to 23,74 kPa (178,06 mmHg), varying on average 2,51 kPa (18,83 mmHg) and 1,79 kPa (13,43 mmHg) of pressure in AVF with anastomosis length 5 mm and 6 mm respectively.

Figure 5 shows the pressure variation data with the anastomosis length of 5 mm, 6 mm and 7 mm at the P1 pressure tap during the AVF experiment.

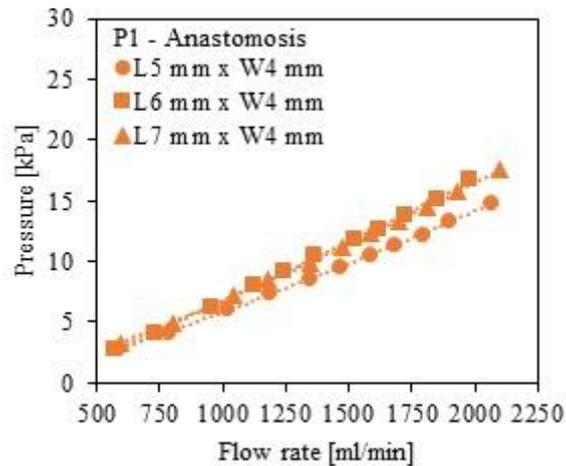


Figure 5. Anastomosis pressure graph by flow rate

It can be noticed an increasing behavior of the pressure as a function of the increase in flow. It is observed that the anastomotic pressure variation between fistulas with anastomotic length of 6 mm and 7 mm is small, with pressure of 2,72 kPa (20,40 mmHg) and 3,34 kPa (25,05 mmHg) increasing 16,78 kPa (125,86 mmHg) and 17,57 kPa (131,79 mmHg), respectively, varying on average 0,69 kPa (5,18 mmHg). However, the fistula with anastomosis length of 5 mm had lower pressure when compared to the L6mm and L7mm fistulas, with a pressure of 2,83 kPa (21,23 mmHg) increasing to 14,78 kPa (110,86 mmHg), varying on average 0,93 kPa (6,98 mmHg) and 1,62 kPa (12,15 mmHg) of the pressure in the AVF with length of 6 mm and 7 mm anastomosis, respectively. Thus, it can be noted that the pressure loss downstream of the anastomosis is greater for fistula with anastomosis length of 5 mm.

Figure 6 shows the pressure variation data with the anastomosis length of 5 mm, 6 mm and 7 mm at the P2 pressure tap during the experiment in the AVF.

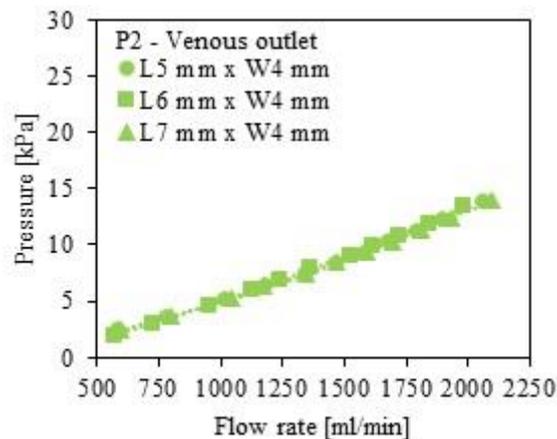


Figure 6. Venous outlet pressure graph by flow rate

It can be noticed an increasing of the pressure as a function of the increase in flow. It is observed that the variation in arterial outlet pressure between fistulas with anastomosis length of 5 mm, 6 mm and 7 mm is small, with pressure of 2,41 kPa (18,08 mmHg), 1,96 kPa (14,70 mmHg) and 2,47 kPa (18,53 mmHg) increasing to 13,86 kPa (103,96 mmHg), 13,46 kPa (100,96 mmHg) and 13,92 kPa (104,41 mmHg), respectively. Thus, it can be noted that the variation in the length of the anastomosis does not influence the pressure upstream of the anastomosis.

To quantify the total resistance, the pressure drop to increase the flow was calculated in the three fistula models, as shown in Figure 7.

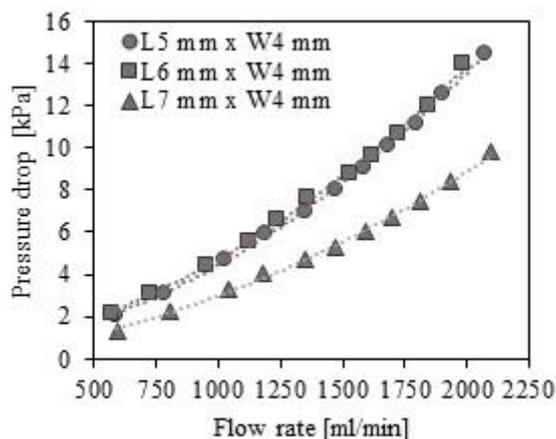


Figure 7. Pressure drop graph by flow rate for different anastomosis sizes, anastomosis angle fixed to 45°.

It can be noticed an increasing behavior of the pressure drop as a function of the increase in flow. It is observed that the variation in the pressure drop between arterial inlet and arterial outlet in fistulas with anastomosis length of 5 mm and 6 mm is small, with pressure drop of 2,07 kPa (15,53 mmHg) and 2,18 kPa (16,35 mmHg) increasing pressure drop of 14,45 kPa (108,38 mmHg) and 13,96 kPa (104,71 mmHg), respectively, varying on average by 0,33 kPa (2,48 mmHg). However, the fistula with an anastomotic length of 7 mm had a lower pressure drop when compared to the L5mm and L6mm fistulas, with an average pressure drop of 1,33 kPa (9,98 mmHg) increasing pressure drop of 9,81 kPa (73,58 mmHg), ranging on average from 4,72 kPa (35,40 mmHg) and 2,30 kPa (17,25 mmHg) of pressure in the AVF with anastomosis length 5 mm and 6 mm, respectively. Thus, it can be noted that the smallest pressure drop in the AVF with longer anastomosis length comes from the depressurization downstream of the anastomosis.

These pressure drops are similar in other AVF works. Hassan et al. (2012), studied the hemodynamic effect of AA with the variation of the size of the anastomosis in pressure drop. The results showed that for the 45° AA there was a small difference in pressure drop between the AVF with anastomosis length of 5 mm and 6 mm, and they presented a greater difference in pressure drop for the configuration with anastomosis length of 7 mm. Thus, the pressure drop behavior in Figure 7 is validated with the literature.

Van Cannes et al. (2010) studied the hemodynamic impact with variation in size and AA. The results showed that the pressure drop decreases with the increase in the transversal area of the anastomosis. In Figure 8, it is possible to visualize the results of the pressure drop for the increase in flow with variation in the size of the anastomosis in the work of Van Canneyt et al. (2010).

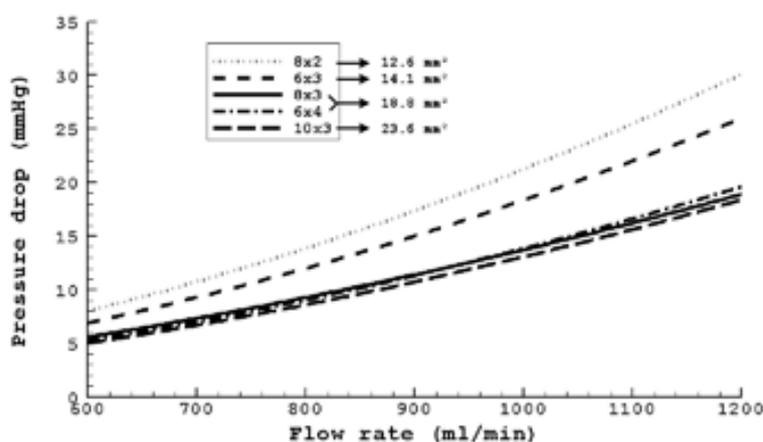


Figure 8. Pressure drop over anastomosis versus blood flow rate for different anastomosis sizes (length x width, both in mm), anastomosis angle fixed to 30°.

The results of Van Canneyt et al. (2010) presented increasing pressure drop to increase the flow, and greater pressure drop in AVF with smaller cross-sectional area. When comparing with Figure 7, a difference can be seen in the intensity of the pressure drop, which can be assumed by variation in the geometry modeling, and fluid parameters considered in the simulation. This answer points to the influence of the anastomosis length to establish the flow resistance of the system.

Therefore, it can be inferred that the control of the AVF anastomosis configuration becomes convenient to determine the energy dissipation through the pressure drop.

4. CONCLUSION

It can be concluded that the data obtained experimentally were in agreement with the results present in the literature. From the results obtained, it was observed that the variation in the size of the anastomosis considerably influences the pressures downstream of the anastomosis, with greater energy dissipation the shorter the anastomosis length. Thus, it can be concluded that depressurization downstream of the anastomosis causes a lower pressure drop in the AVF with a longer anastomosis length. However, the variation in the length of the anastomosis does not influence the pressure upstream of the anastomosis.

Based on these results for the construction of an AVF with 45° AA, the anastomosis length of 7 mm is it presents a lower arterial inlet pressure, less energy dissipation between the arterial inlet and the anastomosis, and smaller changes in system pressure. Finally, this study emphasizes the importance and care that should be taken with the configuration of the anastomosis during the construction of the AVF.

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