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FLOW ANALYSIS IN A FLEXIBLE ARTERIOVENOUS FISTULA MODEL

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Abstract. *The arteriovenous fistula (AVF) is recognized as the best vascular access for patients with chronic renal failure. It is created by surgically connecting an artery and a vein. One of the common complications after its creation is the reduction of blood flow distally due to arterial blood diversion towards the AVF, known as steal syndrome or hand ischemia. This study aims to analyze the pressure field in a flexible AVF model based on data from a real patient under normal flow conditions and with steal syndrome. A flexible AVF model was manufactured using 3D printing mold injection for conducting the research. The experimental data were collected from pressure transducers at 7 access points in the AVF, and a flow sensor located in the inlet pipe before the artery was used for flow measurement. Two flow regimes were analyzed: without steal syndrome and with steal syndrome (thirty percent of the total flow in the anastomosis coming from the distal artery). The results showed that the pressure exhibited a similar behavior in both cases. The pressure was highest at the inlet and decreased until point 3 (anastomosis). At point 4, the pressure increased compared to the previous point and then decreased again until the final measurement point. For the case without steal syndrome, the inlet and outlet pressures were 3.99 kPa and 0.34 kPa, respectively, and the flow measured at the AVF inlet was 2113.3 ml/min ± 89.66 ml/min. In the case with steal syndrome, the inlet pressure was 3.44 kPa, the outlet pressure was 0.30 kPa, and the flow was 1474.5 ml/min ± 56.53 ml/min. It was observed that the pressure differential in the system for the case with steal syndrome was 3.15 kPa, while for the case without steal syndrome, it was 3.66 kPa. These results indicate a lower average pressure in the system when steal syndrome is present.*

Keywords: AVF, Pressure, Flow rate, Pressure drop, Ischemic steal syndrome, Flexible arteriovenous fistula.

1. INTRODUCTION

According to the Brazilian Society of Nephrology census conducted in 2019, the estimated total number of patients undergoing dialysis treatment in Brazil was approximately 140,000. Among the available dialysis methods, hemodialysis (HD) is adopted by 92.2% of the patients in treatment. A recent study conducted by Neves et al. (2021) shows a continuous increase in the number of patients and in the incidence and prevalence rates of dialysis in the country.

The arteriovenous fistula (AVF) is recognized as the best vascular access for patients with chronic renal failure (Krzanowski et al., 2011; Briones et al., 2010; Akoh, 2009). The AVF is created through a surgical connection between an artery and a vein, performed by a vascular surgeon. It allows for an adequate volume of blood flow and an appropriate diameter of the superficial vein for the hemodialysis procedure (Toregeani et al., 2008). The increased blood flow results in high shear forces, leading to vein dilation. These shear forces align the endothelial cells, which function as mechanical sensors triggering the release of relaxation factors such as nitric oxide and prostacyclin, promoting vasodilation and vessel diameter increase (Corpataux, 2002).

Among the advantages of using AVF, notable benefits include the absence of tubes and penetrating catheters on the body surface, the ability to use the arm normally outside HD sessions, no need for prolonged dressings, low risk of infections, as well as simple and quick access to the bloodstream, in addition to being a cost-effective option (Amato, 2019; Gill et al., 2017).

Steal syndrome or hand ischemia is a common and potentially severe complication following AVF creation. Symptoms usually include cooling of the extremity, pain, paleness, muscle fatigue, and decreased or absent distal pulses (Malgor et al., 2007). In severe cases, steal syndrome can even lead to limb loss (Lazarides et al., 2007). Steal syndrome occurs due to the diversion of arterial blood towards the AVF, and according to Stolic (2013), it presents a complication incidence ranging from 2 to 8%.

Considering the relevance and potential consequences of steal syndrome in hemodialysis patients, it is essential to further study this condition. Understanding the mechanisms involved in steal syndrome is crucial for improving the patients' quality of life.

This study aims to analyze the pressure field in a flexible AVF model manufactured based on data from a real patient under normal flow conditions and with steal syndrome.

2. METHODOLOGY

2.1 Data Acquisition, Processing and FAV Manufacturing

For the execution of this work, the flexible AVF model developed by Rangel (2021) was used. Figure 1 shows the schematic of its development.

Rangel (2021) constructed the flexible AVF model with an arterial wall thickness and venous wall of 1 mm. Its geometry was obtained by a computed tomography (CT) scan of the left upper limb of a patient with brachiocephalic AVF. This procedure was performed at the Onofre Lopes University Hospital of the Federal University of Rio Grande do Norte (HUOL-UFRN). Subsequently, the three-dimensional model was made with the aid of the InVesalius software (CTI – Campinas) and the Autodesk Meshmixer software (São Rafael, CA, USA) was used for the treatment of the mesh surface. The flexible AVF was manufactured by injection in a bipartite mold and with internal volume manufactured by 3D printing using ABS filament. After injection and cure of the silicone, the internal volume was removed with acetone of 98% concentration.

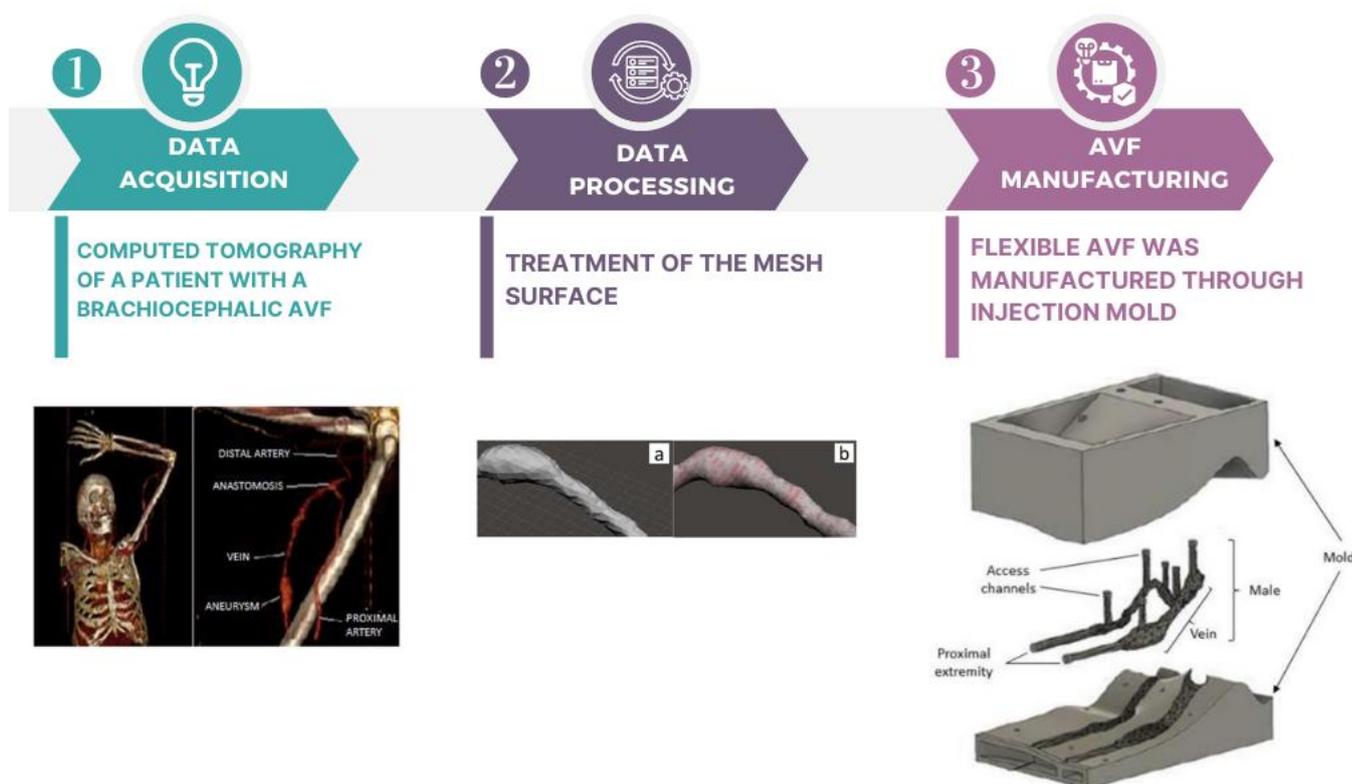


Figure 1. Schematic of the acquisition, processing, and manufacture of the flexible AVF.

2.2 Experimental Workbench

The experimental workbench used was developed at the Laboratory of Fluid Mechanics (LMF – UFRN) with the objective of capturing pressure and flow data at points established in the system for a permanent flow. Figure 2 shows the schematic of the experimental bench.

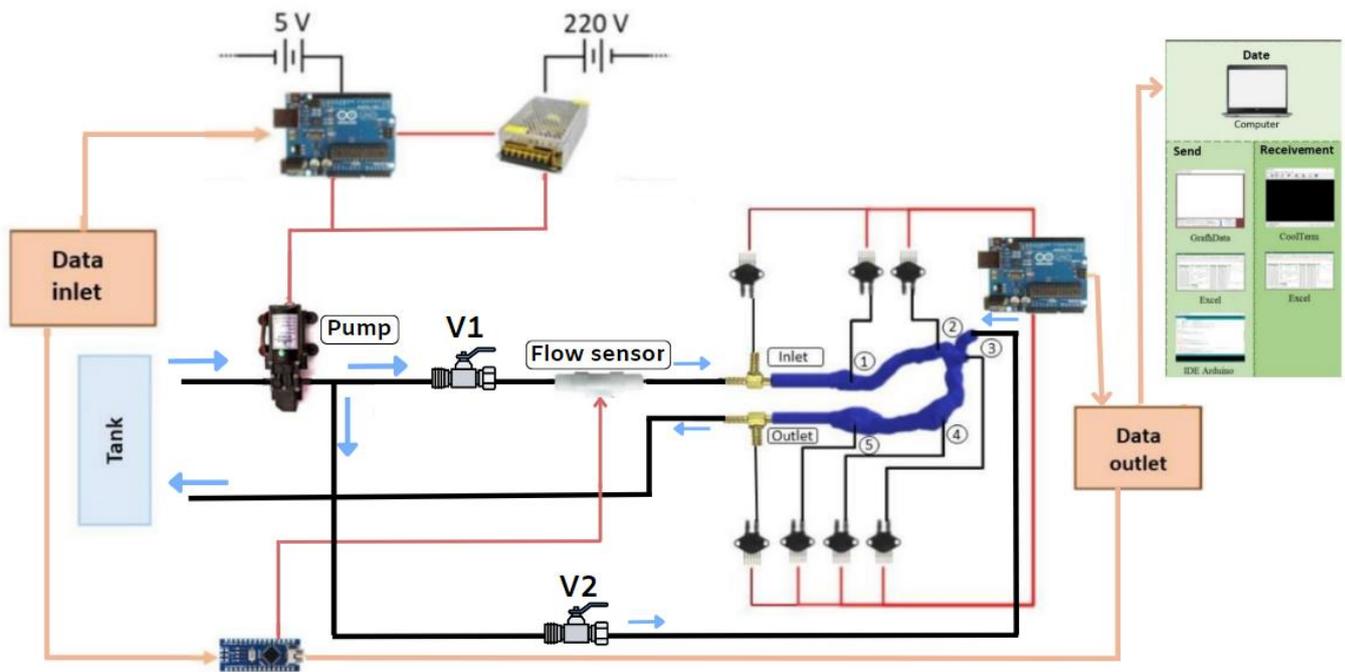


Figure 2. Schematic of the experimental workbench.

To displace the fluid, the RHONDAMAQ pump, model CF-2201^a, was used, with a maximum flow of 4500 ml/min and a maximum pressure of 758.42 kPa (110 psi).

The working fluid was water at room temperature, which circulated through transparent polyvinyl chloride (PVC) hoses of 7 mm diameter and 2 mm thickness. Two globe valves, called V1 and V2, were used to block and partially or totally pass the flow. For pump control and data acquisition, the Arduino Uno microcontroller board was used.

Experimental pressure data were collected from Freescale pressure transducers, model MPX5050DP, at seven access points in the AVF. Figure 3 shows in detail the access points for pressure acquisition. These transducers have a measuring range of 0 to 50 kPa and a measurement uncertainty of $\pm 2.5\%$. In the input and output of the flexible AVF it was necessary to insert rigid connections to obtain the pressure data.

To acquire the flow, a flow sensor of the brand Ultini, model USN-HS41TA, was used, located in the inlet pipe before the artery. This sensor has a reading capacity of 250 to 3000 ml/min and a maximum fluid operating pressure of 0.8 MPa.

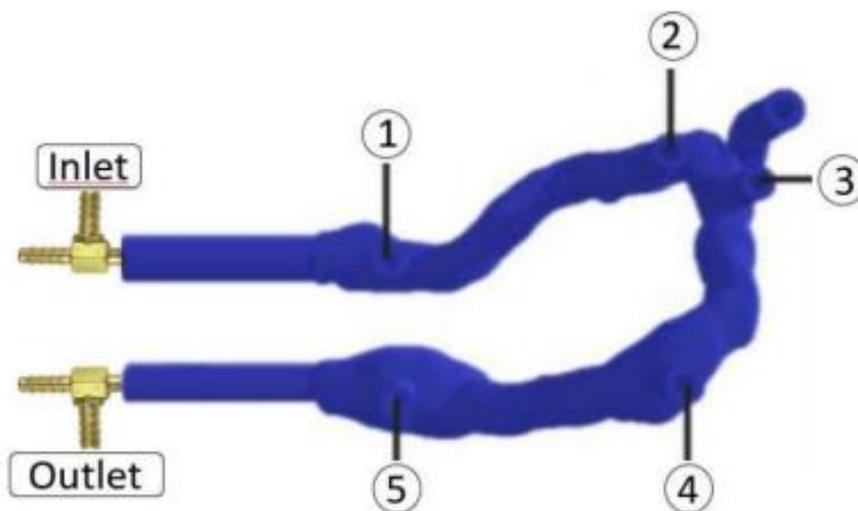


Figure 3. FAV access points.

2.3 Experimental procedure

Two cases were analyzed for steady flow: without steal syndrome and with steal syndrome. In both cases, 80% of the pump's capacity was utilized due to the potential for flexible AVF rupture.

In the case without steal syndrome, valve V1 is fully open, while valve V2 is completely closed. For the case with steal syndrome, a flow rate of 30% of the total anastomotic flow from the distal artery was established. In this case, valve V1 remains fully open, while valve V2 is partially open. The control of valve V2's opening depends on the value registered by the flow sensor.

For the case with steal syndrome, the fluid from the tank passes through the pump and then splits into a bifurcation: one part is directed to the AVF inlet, and the other to the point of anastomosis. The fluid that goes to the AVF inlet passes through the globe valve (V1) and then through a flow sensor before reaching the AVF inlet. The portion directed to the point of anastomosis passes through the globe valve (V2) before entering the fistula. Subsequently, the fluid proceeds to the outlet, where it returns to the tank.

3. RESULTS AND DISCUSSION

Using 80% of the pump load it was possible to obtain the pressure values at the inlet, at the access points 1, 2, 3, 4, 5 and at the outlet of the flexible AVF. Table 1 shows the pressure and flow results obtained in the experiment for cases with and without steal syndrome.

Table 1. Pressure data obtained for cases with and without steal syndrome.

	Pressure (kPa)							Flow rate (ml/min)
	Inlet	1	2	3	4	5	Outlet	
No Steal Syndrome	3.99	3.43	2.97	2.54	2.79	2.50	0.34	2113.3 ± 89.66
With Steal Syndrome	3.44	3.38	2.98	2.65	2.94	2.75	0.30	1474.5 ± 56.53

For the case without steal syndrome, the pressure values range from 3.99 kPa at the inlet to 0.34 kPa at the outlet, so it has a pressure differential of 3.66 kPa. Pressure values gradually decrease as the fluid moves along the AVF. The flow measured at the inlet is 2113.3 ml/min ± 89.66 ml/min for the case without steal syndrome.

In the case with steal syndrome, the pressure values range from 3.44 kPa at the input to 0.30 kPa at the output, so it has a pressure differential of 3.15 kPa. Pressure values also decrease throughout the AVF. The flow at the entrance, for the case with steal syndrome, is 1474.5 ml/min ± 56.53 ml/min.

Note that the pressure differential in the system for the case with steal syndrome (3.15 kPa) was lower than for the case without steal syndrome (3.66 kPa). These results indicate a lower average pressure in the system when steal syndrome is present.

In the condition without steal syndrome, the pressure measured at the entrance of the AVF was 3.99 kPa, while in the case with steal syndrome, the pressure was slightly lower, at 3.44 kPa. A pressure difference of 0.55 kPa.

At point 1 (arterial segment), the pressure was 3.43 kPa for the case without steal syndrome and 3.38 kPa for the case with steal syndrome, resulting in a pressure difference of 0.05 kPa.

At point 2 (arterial segment), the pressure was 2.97 kPa for the case without steal syndrome and 2.98 kPa for the case with steal syndrome, resulting in a pressure difference of -0.01 kPa.

At point 3 (anastomosis), the pressure was 2.54 kPa for the case without steal syndrome and 2.65 kPa for the case with steal syndrome, resulting in a pressure difference of -0.11 kPa.

At point 4 (venous segment), the pressure was 2.79 kPa for the case without steal syndrome and 2.94 kPa for the case with steal syndrome, presenting a pressure difference of -0.16 kPa.

At point 5 (venous segment), the pressure was 2.50 kPa for the case without steal syndrome and 2.75 kPa for the case with steal syndrome, a pressure difference of -0.24 kPa.

At the AVF output, the pressure was 0.34 kPa for the case without steal syndrome and 0.30 kPa for the case with steal syndrome, a pressure difference of 0.04 kPa.

In Figure 7, we have the graph with the pressure data of each access point for the cases.

Note that for both cases the pressure has a similar behavior. The pressure is maximum at the inlet and gradually decreases to point 3 (anastomosis). At point 4 the pressure increases in relation to the previous point and then returns to a decreasing behavior until the last measuring point (output).

It was also observed a lower pressure at the entrance of the AVF and at points 1 and 2 for the case with steal syndrome compared to the one without steal syndrome, due to the lower flow at the entrance to the AVF.

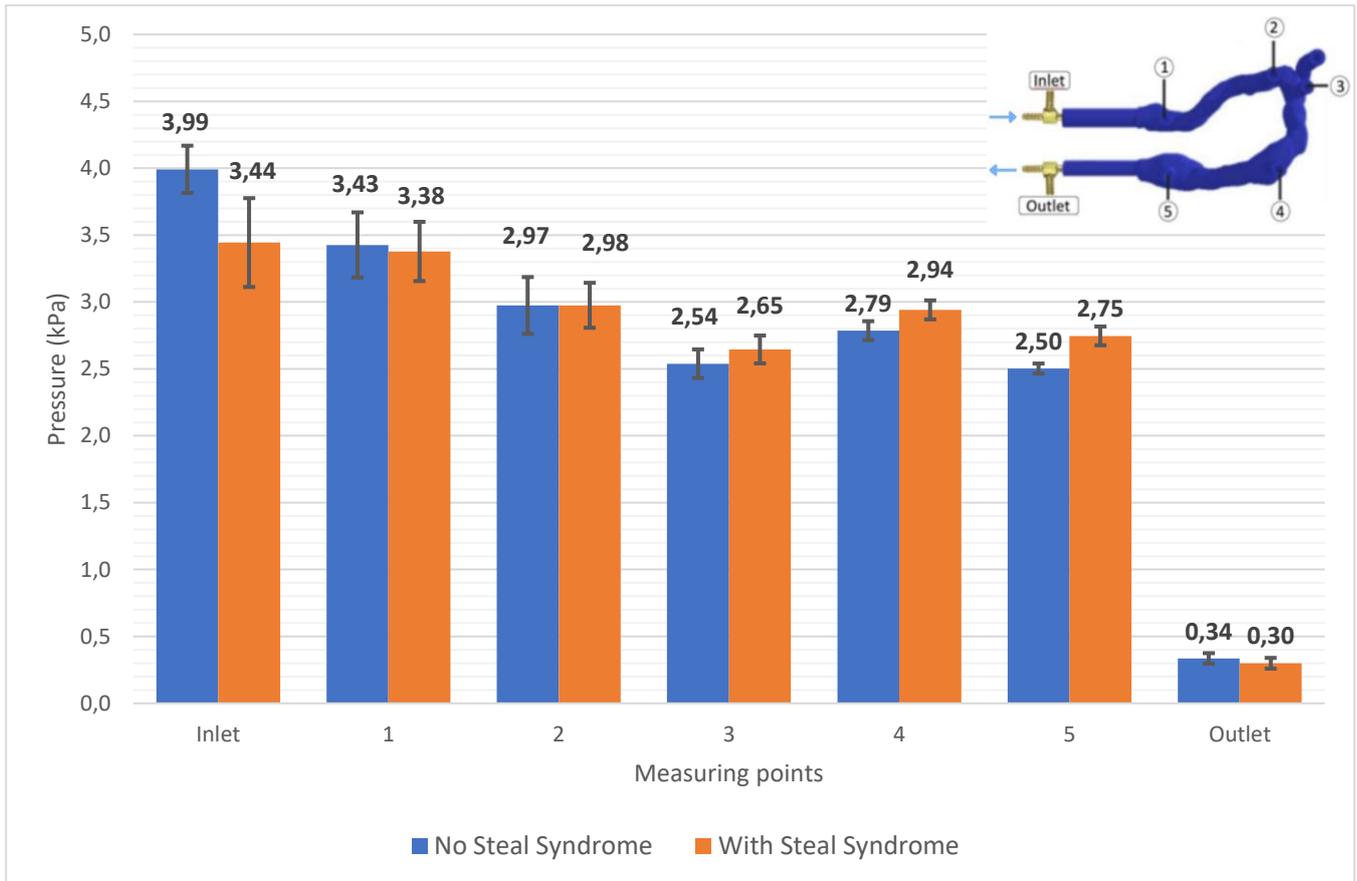


Figure 4. Graph of pressure data obtained for the case without steal syndrome and with steal syndrome.

The increased pressure at points 4 and 5, venous segment, may be related to the location. Such points have a larger cross-sectional area due to aneurysms. The abrupt change of the vessel due to the aneurysm, anastomosis and its irregular geometry may have caused regions of recirculation near the walls. According to the principle of conservation of mass in incompressible fluids, when the cross-sectional area increases, the flow velocity decreases, resulting in an increase in local pressure (Fox et al., 2015).

At the output, for both cases, there is a more pronounced pressure drop due to the area restriction and rigidity of the connection used to access the measuring point.

In the studies conducted by Rangel et al. (2023) for a flexible AVF with a wall thickness of 1 mm, the following pressure values were obtained at points 1, 2, 3, 4 and 5: 15.16 kPa, 14.25 kPa, 13.03 kPa, 13.56 kPa and 13.64 kPa, respectively. It is noted that the pressure values are significantly higher compared to those obtained in this study.

The highest pressure value obtained in the experimental data was 3.99 kPa. However, it is important to note that the pressure transducers used have a measuring range ranging from 0 kPa to 50 kPa, that is, the maximum value recorded is outside the ideal measuring range of the transducer.

4. CONCLUSION

Based on the results obtained experimentally, we verified a pressure behavior for the case without steal syndrome like that with steal syndrome. The increase in pressure at points 4 and 5 (venous follow-up) must be related to the increase in vessel diameter, abrupt vessel change, anastomosis, and irregular geometry, which can cause regions of recirculation. The use of a pressure sensor outside the ideal range may be causing errors in the measurements. The results indicate a lower average pressure in the system when steal syndrome is present.

5. ACKNOWLEDGEMENTS

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