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# FLOW ANALYSIS IN RIGID AND FLEXIBLE ARTERIOVENOUS FISTULA MODELS

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***Abstract.*** *Arteriovenous fistula (AVF) is the most commonly used vascular access (VA) for the treatment of hemodialysis. Even though AVF is the most used VA it can suffer problems due to its construction and use. High shear stresses and recirculation zones (related to the change in geometry and flow parameters in the vessels after the creation of the AVF) contribute to the appearance of pathologies that may render the VA unusable. In order to relate the flow conditions and the geometry of the VA with the possible appearance of pathologies the work proposes to analyze experimentally the flow in rigid and flexible AVF models constructed from real data of a patient. From the computed tomography of the patient the cleaning and selection of the VA region were performed from which AVFs rigid and molds were manufactured for the production of silicone AVFs. Based on the input pulses, there was an increase in pressures at the points following the first point in both cases. Regarding rigid and solid AVF, for the same point, there is a significant difference between the values for flexible AVF (higher) and rigid AVF (lower).*

***Keywords:*** *arteriovenous fistula, shear stress, experimental analysis, pressure field.*

## 1. INTRODUCTION

Hemodialysis is considered by some authors as the main form of treatment for patients suffering from chronic renal failure (CRF) (Javadzadegan *et al.*, 2017; Villiers *et al.*, 2018), treatment which necessitates a vascular access to the bloodstream that provides an increase in blood flow conditions for good dialysis (Javadzadegan *et al.*, 2017).

Several studies suggest that arteriovenous fistula is the best vascular access for patients on hemodialysis because it is a durable and low complication rate access (Krzanowski *et al.*, 2011; Briones *et al.*, 2010; Akoh, 2009).

Although it is considered the better VA for hemodialysis treatment, the AVF may come to suffer some problems arising from its creation and its use due to the new flow conditions imposed on it, such examples are: pseudoaneurysms, hand edema, neointimal hyperplasia between others.

After the design of the vascular access new non-physiological flow conditions and hemodynamic disturbances are imposed on the AVF causing the problems. Disturbances such as pathophysiological zones of shear stress of the wall and flow recirculation are fundamental for the appearance of these complications (Javadzadegan *et al.*, 2017).

Problems such as stiffness of the vascular walls also influence in a significant way the response of the blood vessels to the change in the requests undergone by the same ones, being indispensable its study for the understanding on the phenomena that permeate the blood flow and changes in the same with the creation of the AVF.

This paper seeks to establish the relationship between geometric and flow parameters in a vascular access of a real patient with possible pathological conditions.

## 2. METHODOLOGY

The present work will analyze experimentally the flow in vascular access models. A cardiovascular pulse workbench will be used in which the AVF will be tested in order to compare the results obtained with those present in the literature. It may be possible to establish a direct relationship between the flow parameters and geometry of the AVFs with the recurring problems in them.

### 2.1 Data Acquisition and Processing

Data were obtained from computed tomography (CT) of a patient with CRF through the University Hospital Onofre Lopes - HUOL of the Federal University of Rio Grande do Norte - UFRN. Three-dimensional reconstruction, cleaning and selection of the AVF region were performed from the CT data. Figure 1:


Figure 1. Reconstruction, cleaning and selection of the AVF region

After reconstruction, cleaning and AVF selection, the virtual mesh generated was improved due to the significant amount of CT elements and the moderate computational capacity of the computer. Some closure problems in the mesh were later corrected beyond the superficial smoothing of the virtual model.

### 2.2 Manufacture of AVFs

The rigid AVF was fabricated by rapid prototyping (3D printing) with a wall thickness of 3 mm and access points for pressure transducers and instrumentation in general. The filling used was 100% (relative to the density of the wall of the AVF press) in order to guarantee a greater rigidity to the manufactured VA.

For the design of the flexible AVFs, a two-part mold made by rapid prototyping was developed where through the silicone injection with a negative internal volume of the AVF centered inside the mold, the flexible VAs will be manufactured. See the mold scheme in Figure 2.

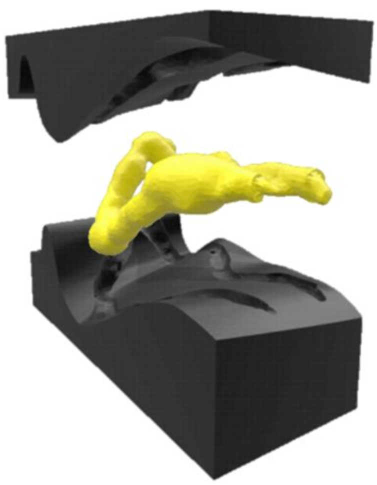

Figure 2. Mold for the manufacture of flexible AVF

## 2.3 Pulsatile flow workbench

The developed experimental bench simulates cardiovascular pulse and is composed of a diaphragm pump, flow regulating valves, reservoir, piping system, pump control system and data acquisition system.

The acquisition system consists of a microcontroller (*ESP-32*) and pressure sensors (*MPX5050DP*). The layout of the experimental bench is shown in Figure 3.

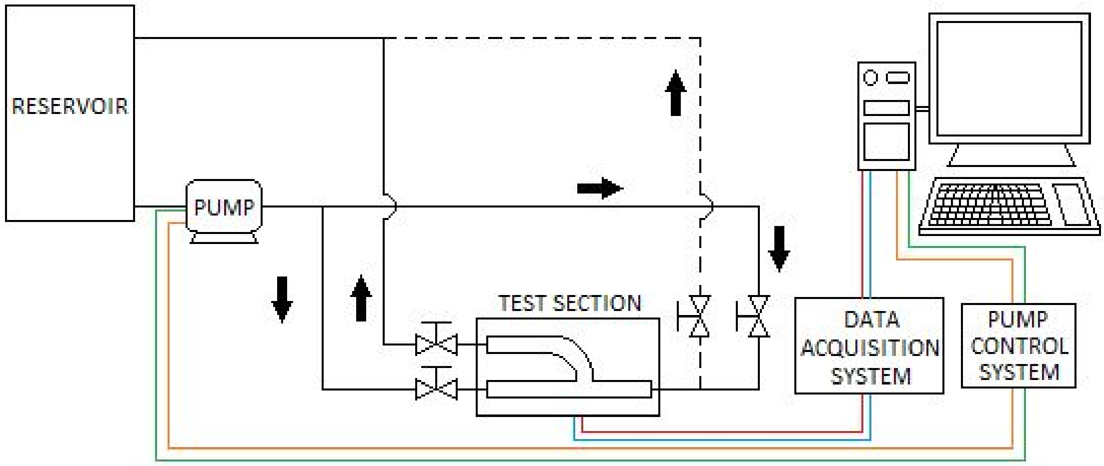


Figure 3. Pulsatile flow workbench (layout)

Pump operating parameters allow you to create pulse models based on the displaced volume and diaphragm speed. The pump is driven by controlled by an *Arduino Uno* microcontroller. The pump control system allows the variation of the supply voltage through a transistor thus generating the desired pressure pulse, similar to the physiological one.

## 2.4 Experimental procedure

Five points were selected to capture the pressures: two in the artery, one in the anastomosis and two in the vein in regions of possible aneurysms. A specific analysis of pressure pulse in different regions of rigid AVF and flexible AVF is desired.

The flow imposed by the system is from (1) to (5), with no flow contribution at the near inlet of the anastomosis (distal artery). The schematic drawing of the AVF with the collection points is shown in Figure 4.

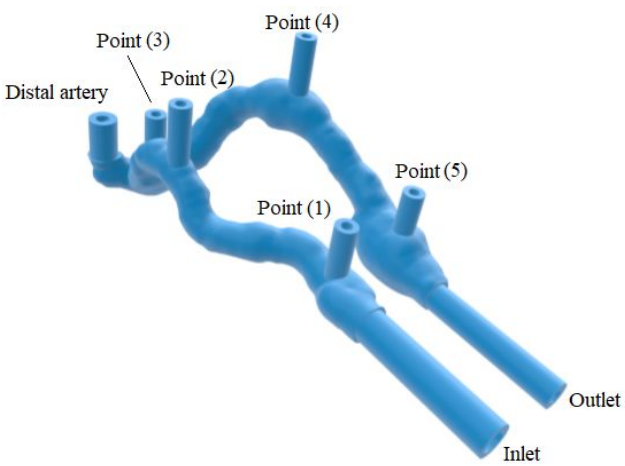


Figure 4. AVF schematic drawing - Collection points

After the manufacturing of the AVFs, the tests were performed with the pulse value generated in the system and the pressure pulses were acquired at the selected points. The pulse generated at the rigid and flexible entry of FAVs based on previous system calibrations is shown in the Figure 5.

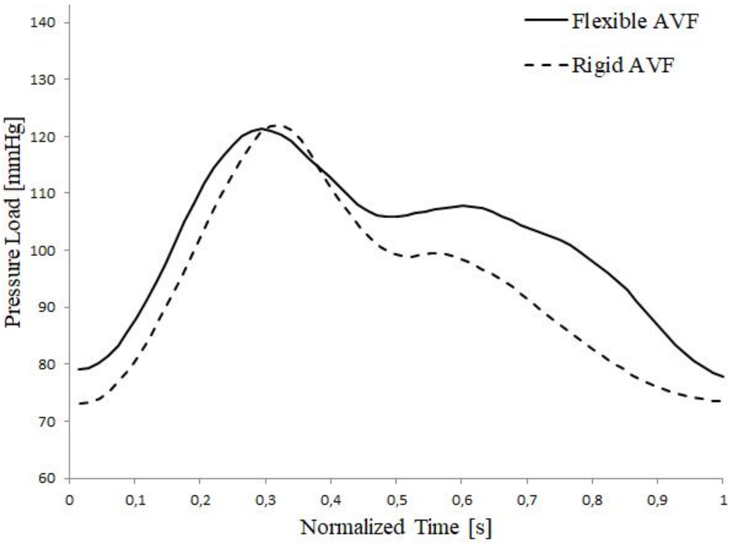


Figure 5. Pressure Pulse - Point 1 (Input)

The calibrated pulse based on the flexible fistula input takes into account the initial deformation present in the system and therefore there is a difference in the composition, manner of obtaining and implementing the pulse in rigid and flexible AVFs. The pulse developed for application in both systems met the maximum load characteristics of approximately 120 mmHg and minimum load of approximately 80 mmHg for flexible AVF and approximately 73 mmHg for rigid AVF in a normalized period.

## 3. RESULTS AND DISCUSSION

Rigid AVF models were obtained for the bench test from rapid prototyping. The 100% padding on VA wall printing was chosen based on preliminary tests in which the AVF with the lowest fill percentage in the manufacture resulted in breakage during bench calibration and experimental analysis. Access points to obtain pressure were drawn on the actual vessel in regions where possibly the most severe requests are likely to be located. Figure 6.

Figura 6. Rigid AVF

Flexible AVF was obtained by fabricating the hollow split mold medium manufactured by rapid prototyping, in which a negative internal volume of the real AVF also printed in 3D was inserted. Centering the AVF in negative, silicone was poured into the mold to fill the void between the system components, trying to avoid voids and the presence of air bubbles. Note the bottom of the mold with the manufactured flexible AVF in the Figure 7.

Figure 7. Flexible AVF in the mold

The presence of air bubbles in the system and the complex geometry were the difficulties for the manufacture of silicone AVF. In order to establish the strain ratio present in real arteriovenous fistulae, a value of 4.29 µm was calculated for which the thickness of silicone AVFs should be fabricated in order to undergo the same deformations of actual AVFs, using data extracted from Sorace *et al.* 2012.

It was not possible to manufacture the AVF with these dimensions due to technological limitations, so we chose the value of 3 mm for the manufacture of silicone AVFs because it is more tangible and easy to manufacture.

After the application of the developed pulses (Figure 4), the pressure pulses were collected at the selected points. Figure 8 shows the pulses collected at the points in the rigid and flexible AVF respectively.

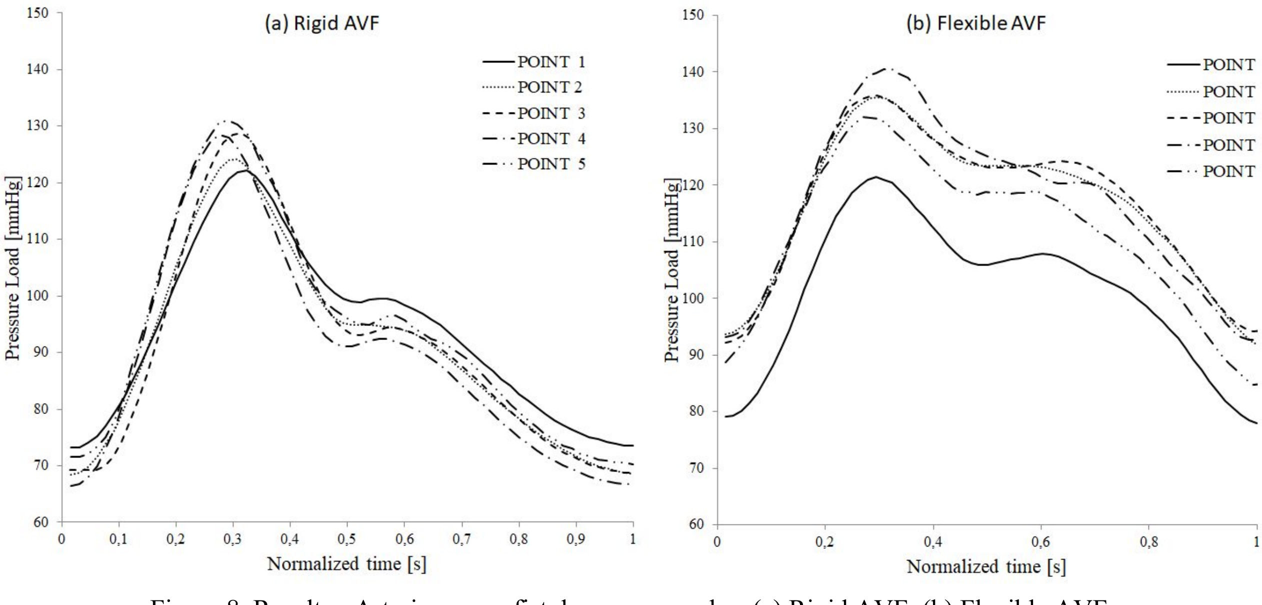


Figure 8. Results - Arteriovenous fistula pressure pulse: (a) Rigid AVF; (b) Flexible AVF

In flexible AVF there is an increase in the pressure pulse at all points relative to the inlet pressure (point (1)). At point (2), the point allocation itself indicates that part of the dynamic pressure is being measured by the pressure sensor and is a favorable area for recirculation in the VA.

Point (3) represents the anastomotic region that in previous computer simulations developed in VA showed it as a chaotic flow and recirculation region. According to the pulse collected in this region there was an increase in pressure compared to the pressure at point (1). The pressure pulse collection point is situated approximately in the center of the artery-vein union, possibly flow disturbances in this region may be implying the high pressure which was being expected for this region of the system.

The pressures collected at points (4) and (5) were higher when compared to those at point (1). For point (4), the point with the highest pressure value reached, it is suspected that as well as point (2) the geometry of this region and transducer point arrangement has caused some of the dynamic flow pressure in that region to be being read by the sensor, providing a high pressure. High values were expected for point (4) and point (5).

Points (4) and (5) show an increase in pressure according to the increase in area, being present in these two regions possible aneurysms resulting from punctures for hemodialysis treatment. Geometric readjustment suggests that these regions are subjected to adverse flow conditions from treatment and may be subjected to adverse shear stresses, fluid recirculation and high pressure, among other problems that may cause VA pathology.

In rigid AVF, close proximity between the pulses collected at different points of the VA is observed. In the region between the normalized time of approximately 0.15 to 0.45 occurs a change in the behavior of the pressure pulse values, with the maximum pressure comprised in the pulse of point (1) being the lowest, following in increasing order the point ( 2), (4), (3) and the largest being at the point pulse (5), as shown in figure 7 (a).

As the area ratio in the rigid AVF is fixed in the section for any pulse pressure values we can analyze based on the variation in the area the velocity variation and consequently pressure.

In points (1), (2), (4), (3) and (5) respectively, there is an increasing variation in the area corroborating the decrease in velocity in order to maintain the flow. Thus with decreasing velocity an increase in the pressure value is observed.

Regarding rigid AVF, the data extracted for the pressure pulse in flexible AVF suggests a pressure increase due to deformation and its influence on flow. We can infer that the increase in internal volume due to deformation locally increases the pressure value for the case. The comparisons of pressure pulse values for the rigid and flexible AVFs points can be see in the figure 9.

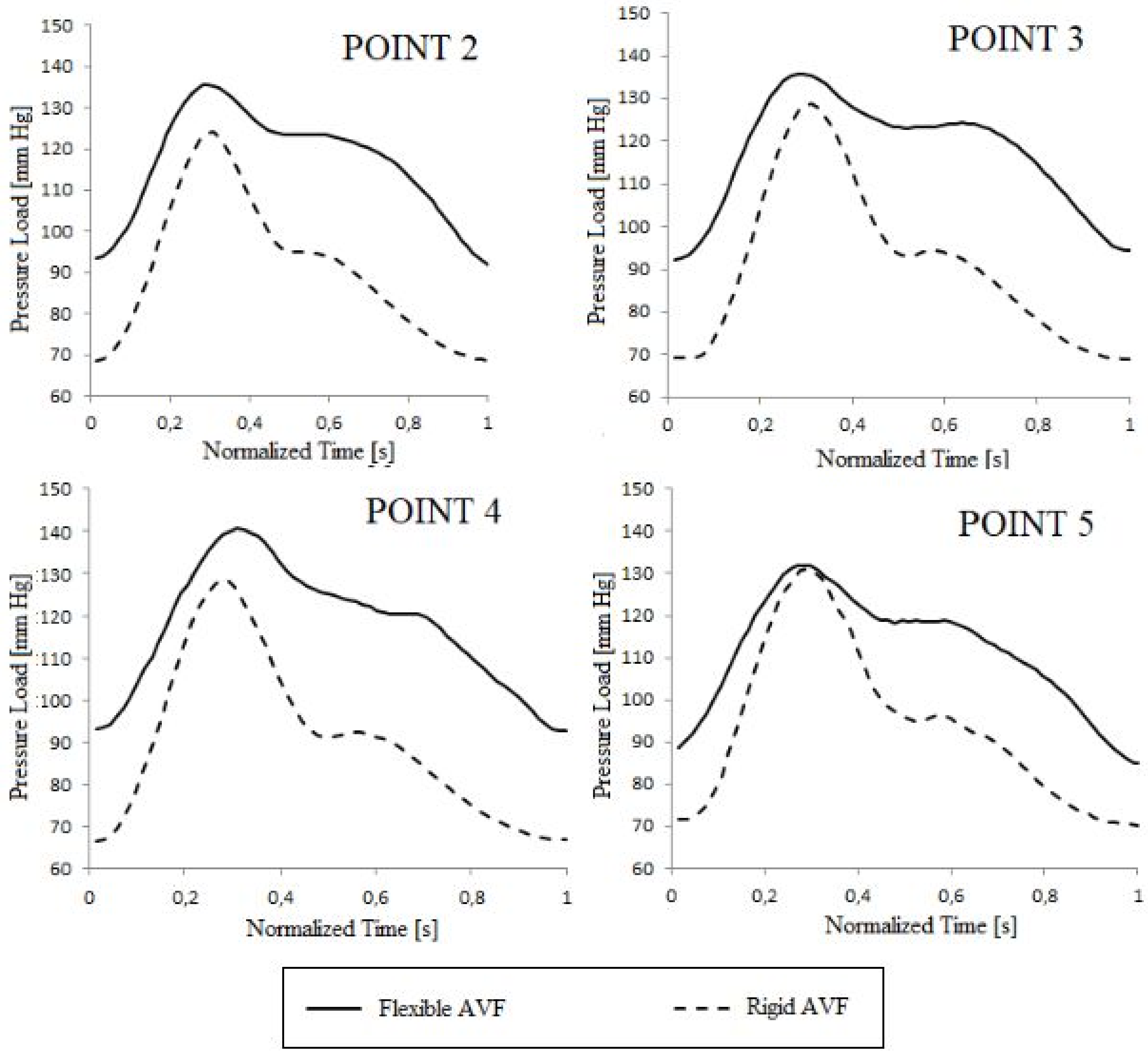


Figure 9. Results - Pressure pulse at the points (2), (3), (4) and (5) (Rigid AVF x Flexible AVF)

Pressures at the same point in the rigid and flexible fistula show discrepancies with each other. Elevation is observed at all points after point (1) in the pulse value in flexible AVF compared to rigid AVF. Volume variation due to deformation, a fact discussed above, may have implicated the pulse locally causing the pressure elevation.

The increase local area in the flexible AVF due to flow may have resulted in a smaller velocity value consequently increasing the pressure.

Flow pulses were not collected due to difficulty in implementing a suitable sensor which should have the ability to collect flow data in a short time. The analysis of these data may confirm the above issues related to local velocity and pressure in the AVF.

More reliable results cannot be taken from the analysis between the numerical values collected in the two types of AVFs due to non-convergence of the pulses implemented in the VAs. The behavior of the pulses allows the previously discussed analyzes, but specific data will be more conclusive when both pulses implemented in the access inputs have the same behavior over time.

## 4. CONCLUSION

Experimental benchtop results offered coherent pulses regarding the conditions imposed on the system. These results show that the fidelity of the system when reproducing mimetic pulses to the physiological pulses will allow the coherent analysis of the AVFs regarding the specific pulse of that region in the cardiovascular system of the patient.

Based on the specific results, reciprocity between the generated and the expected results was observed, observing the behavior of the pulses in relation to each other. However, the coherence of the results obtained can only be reliably affirmed if the input pulses of both AVFs are the same.

The manufacturing process of flexible AVFs opens up a range of options for the creation, analysis and implementation of vessels and artificial biomedical devices, based on their anatomical geometry, providing a better bioadaptation by the patient's organism.

The development of the work, besides helping to study and improve the quality of life of patients with CRF, allow it (with the construction of the experimental workbench) to analyze other regions of the vascular system covering the experimental study in silico on the whole system of blood supply.

## 5. ACKNOWLEDGEMENTS

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