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MODELING OF ARTERIAL CLIPPING BY FINITE ELEMENT METHOD

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Abstract. The Bioengineering is increasingly present in the fields of scientific research worldwide. It gives answers with high accuracy for problems that often have great difficulty in experimental studies in the laboratory. For this purpose, this study proposes to measure the force exerted by a surgical clip when it is applied in a given region in order to occlude arterial blood flow. This force was measured using a computer simulation, which was built by modeling two cylinders, one representing the arterial wall and the other in this first, representing the blood. This simulation was carried out under the coupling between the two domains using fluid-structure interaction. We used a numerical model of three-dimensional flow inside a cylinder of elastic. The fluid is considered incompressible and Newtonian and is governed by the Navier-Stokes equations. The walls of the structure are modeled from the Hooke's Law. A numerical solution is developed using the finite element method to calculate the pressure fields and fluid velocity, displacement field of the structure and the force applied by the clip for the occurrence of obstruction of blood flow at that location.

1 INTRODUCTION

A major problem that affects the most of the world's population is cardiovascular disease, such as vascular disease. Research shows that in the year 2020, both diseases will represent the percentage of death in 35% of population in developed countries and 25% of population in developing countries. Therefore, this paper study the blood circulatory system to contribute in the solution of problems related to blood vessels, also known as aneurysms, which are presented by congenital malformation of the vessel or even diseases acquired during life. This study provides a model of the artery in operation with blood flow through it, and then to discover how make an occlusion of this artery using surgical clip.

An aneurysm is a focal dilation of a blood vessel to greater than 50% of its normal diameter. Aneurysms are most commonly found in the abdominal aorta where major complications may develop without definite warnings. Traditionally, a maximum diameter criterion of 5.5 cm has been employed for abdominal aortic aneurysms to indicate the need for surgical intervention in order to prevent rupture.

Thus, the bioengineering presents itself as another opportunity for research to solve major problems with the aneurysm, thus contributing to a better quality of life.

The tactile and mechanical properties of tissue hold a wealth of information about the physiology and health of that tissue. Surgeons rely a great deal on intuition gained by the “feel” of tissue (a combination of visual and tactile feedback) while performing operations and diagnosing disease. However, as the size of the operating area is reduced, the feedback a surgeon receives from a tissue decreases. During many microsurgical procedures, the blood vessels must be occluded to halt blood flow through the exposed area. Excess force may unintentionally be applied when performing delicate operations such as closure of these vessels or exposure of the vascular endothelial surface (both necessary precursors to several procedures), and this excess force may cause tissue damage, one of the major factors affecting the surgical outcome. Numerous earlier investigations reporting blood vessel damage due to excess force motivated us to develop a microsurgical assistant. In essence, it is a device that provides additional feedback about the blood vessel patency to the surgeon.

Previous experiments explored the mechanical properties of blood vessels. Other studies have used those results to determine the minimum occlusion force (MOF), the force at which the blood vessel is held closed (with no excess being applied). This is of particular importance because microvascular clamp procedures can inflict considerable endothelial damage and creates a concomitant threat of postoperative thrombosis at the lesion site, as shown by several scanning electron and light microscopy studies.

These studies showed that the initial changes in the endothelium occurred in smaller raddi of curvature, and that the possibility and extent of damage is directly related to the applied clamping force. However, the total view of the tissue in vivo has been neglected, as have possible feedback mechanisms for informing the surgeon about the status of the vessel. Possible applications of intraoperative deformation monitoring include cardiovascular surgery, cerebral revascularization and plastic/reconstructive procedures. To be of any to a surgeon, real time calculation of the MOF or closure status of a vessel must be performed.

Therefore, this paper proposes to model the prediction of possible aneurysms celebrate or abdominal aorta. In this study we used a computational tool in engineering. The software simulated the behavior of an arterial segment with its properties and characteristics, when subjected to occlusion of blood flow due to rupture of an aneurysm.

2 MATHEMATICAL MODELING

Mathematical modeling of the problem was based on two separate domains (fluid and structure). It was necessary numerical methods to solve the mathematical equation of geometry (solid and fluid) in cylindrical coordinates (3D) and transient regime. In the interaction between these two domains, we considered at interface the balance of forces and speeds. It was used for the coupling of these domains the technique named as Arbitrary Lagrangian-Eulerian (ALE). The Figure 1 illustrates the solid domain discretized into finite elements and the fluid domain also discretized suffering actions of arterial pressure.

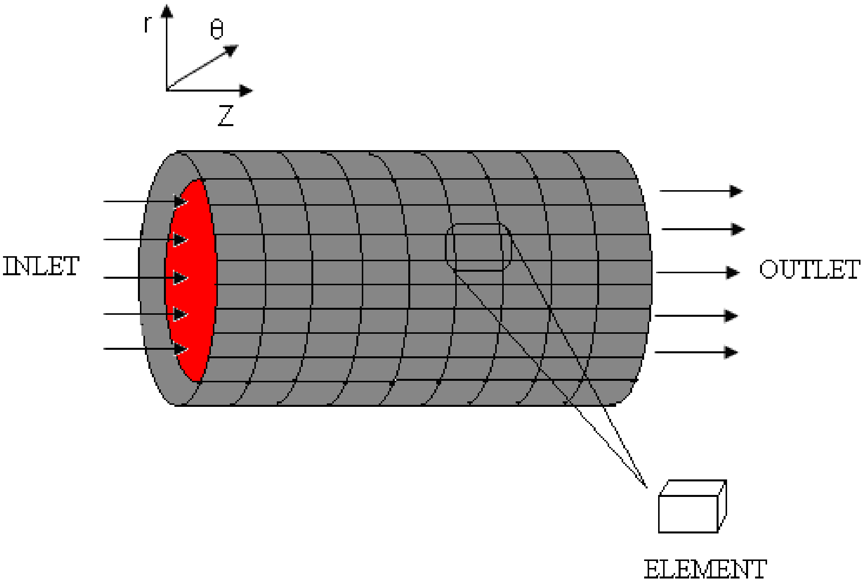

Figure 1: Model of the problem

2.1 Fluid Domain

The equation of mass conservation:

$$\frac{1}{r}\frac{\partial(rV_r)}{\partial r}+\frac{1}{r}\frac{\partial(V_\theta)}{\partial\theta}+\frac{\partial(V_Z)}{\partial Z}=0 \tag{2.1}$$

where:

V_r - Velocity component in r direction
V_θ - Velocity component in θ direction
V_z - Velocity component in z direction

Already the equation of momentum conservation is described as:

Component r:

$$\rho\left(\frac{\partial V_r}{\partial t}+V_r\frac{\partial V_r}{\partial r}+\frac{V_\theta}{r}\frac{\partial V_r}{\partial \theta}-\frac{{V_\theta}^2}{r}+V_z\frac{\partial V_r}{\partial z}\right)= \\ -\frac{\partial p}{\partial r}+\mu\left\{\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}\left[rV_r\right]\right)+\frac{1}{r^2}\frac{\partial^2 V_r}{\partial \theta^2}-\frac{2}{r^2}\frac{\partial V_\theta}{\partial \theta}+\frac{\partial^2 V_r}{\partial z^2}\right\} \tag{2.2a}$$

Component θ:

$$\rho\left(\frac{\partial V_\theta}{\partial t}+V_r\frac{\partial V_\theta}{\partial r}+\frac{V_\theta}{r}\frac{\partial V_\theta}{\partial \theta}-\frac{V_r V_\theta}{r}+V_z\frac{\partial V_\theta}{\partial z}\right)= \\ -\frac{1}{r}\frac{\partial p}{\partial \theta}+\mu\left\{\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}\left[rV_\theta\right]\right)+\frac{1}{r^2}\frac{\partial^2 V_\theta}{\partial \theta^2}+\frac{2}{r^2}\frac{\partial V_r}{\partial \theta}+\frac{\partial^2 V_\theta}{\partial z^2}\right\} \tag{2.2b}$$

Component z :

$$\rho\left(\frac{\partial V_Z}{\partial t}+V_r\frac{\partial V_Z}{\partial r}+\frac{V_\theta}{r}\frac{\partial V_Z}{\partial \theta}+V_Z\frac{\partial V_Z}{\partial Z}\right)= \\ -\frac{\partial p}{\partial z}+\mu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 V_z}{\partial \theta^2}+\frac{\partial^2 V_z}{\partial z^2}\right\} \tag{2.2c}$$

Da qual:

p - Local pressure
r - Radial length
μ - Dynamic viscosity of the fluid
ρ - Fluid density

2.2 Structure Domain

The structure is considered viscoelastic and isotropic. Thus, the Navier equation is:

$$(\lambda+\mu)\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(ru)\right)+\mu\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right)\right)=0 \tag{2.3}$$

Where λ e μ are called Lamé constant, λ describes the shear tension due to variation in density whereas μ is known sometimes as shear modulus of the material.

The elasticity modulus E and Poisson ratio υ may be related to the Lamé constants through the following relations:

$$\upsilon=\frac{\lambda}{2(\lambda+\mu)}, \qquad E=\frac{\mu(3\lambda+2\mu)}{(\lambda+\mu)} \tag{2.4}$$

$$\lambda=\frac{E\upsilon}{(1+\upsilon)(1-2\upsilon)}, \qquad \mu=\frac{E}{2(1+\upsilon)} \tag{2.5}$$

2.3 Fluid Structure Interaction

The boundary conditions that occur at the interface between the two domains of fluid and structure are:

$$v = \frac{\partial u}{\partial t} \tag{2.6}$$

$$\sigma_{rr}{}^{f} \cdot n_r = \sigma_{rr}{}^{e} \cdot n_r \tag{2.7}$$

Where n_r is the unit normal vector out of the plan, $\sigma_{rr}{}^{e}$ is the tension on the inner wall structure and $\sigma_{rr}{}^{f}$ is due to the tension on the inner wall due to the components of the fluid.

2.4 Boundary Conditions

Inlet and outlet pressures are known. The layer of fluid in contact with the arterial wall, has no displacement in the longitudinal direction, so its velocity in this direction (vz = 0) is zero. Interface, where there is a coupling fluid and structure, it is necessary that the displacements are interactive between their domains. The artery has the following characteristics (Canic, 2006; Ibrahim, 2006):

Inner Diameter: 20 mm
Length: 15 cm
Elasticity Modulus: 1.5 x 10^6 Pa
Reference Pressure: 10356 Pa
Fluid Density: 1050 kg/m^3
Fluid Viscosity: 3,5 X10^{-3} Pa s
Clip width: 5 mm

3 RESULTS

At this stage, clips are applied with particular force on the artery in order to occlude blood flow. The clip must have the same strength as required for its function, because any change beyond that required can be disastrous for the outcome of surgery. If the clip applied, have strength below the required, for example, the flow is not interrupted and the clip can escape during the surgery. If on the contrary, the clip has a force far above that required, the artery may be damaged physically taking the patient to have postoperative complications. Figure 2 shows the application of a clamp on an arterial region.

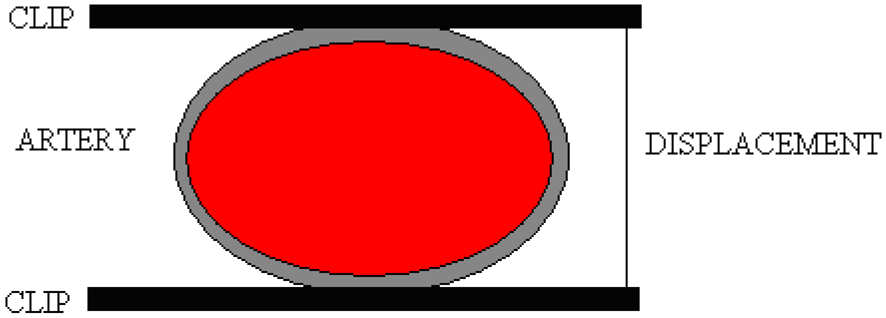

Figure 2: Application of the clamp for arterial occlusion

In considering this application of clips was performed several simulations varying the displacement of the clip toward the radial artery to analyze the behavior of the artery, as well as their reactions to the forces applied to the occlusion.

The arterial wall has suffered displacement due to stresses generated by blood pressure that moment of time. In the end, the arterial wall was fixed, not allowing movement in any direction. The pressures were taken:

Systolic Pressure: 7244,14 Pa (54,34 mmHg)

Diastolic Pressure: 2155,29 Pa (16,17 mmHg)

These pressures are shown in Figure 3, where they compared the blood pressures simulated numerically in this work with the pressures of the experiment obtained by Machado [2010].

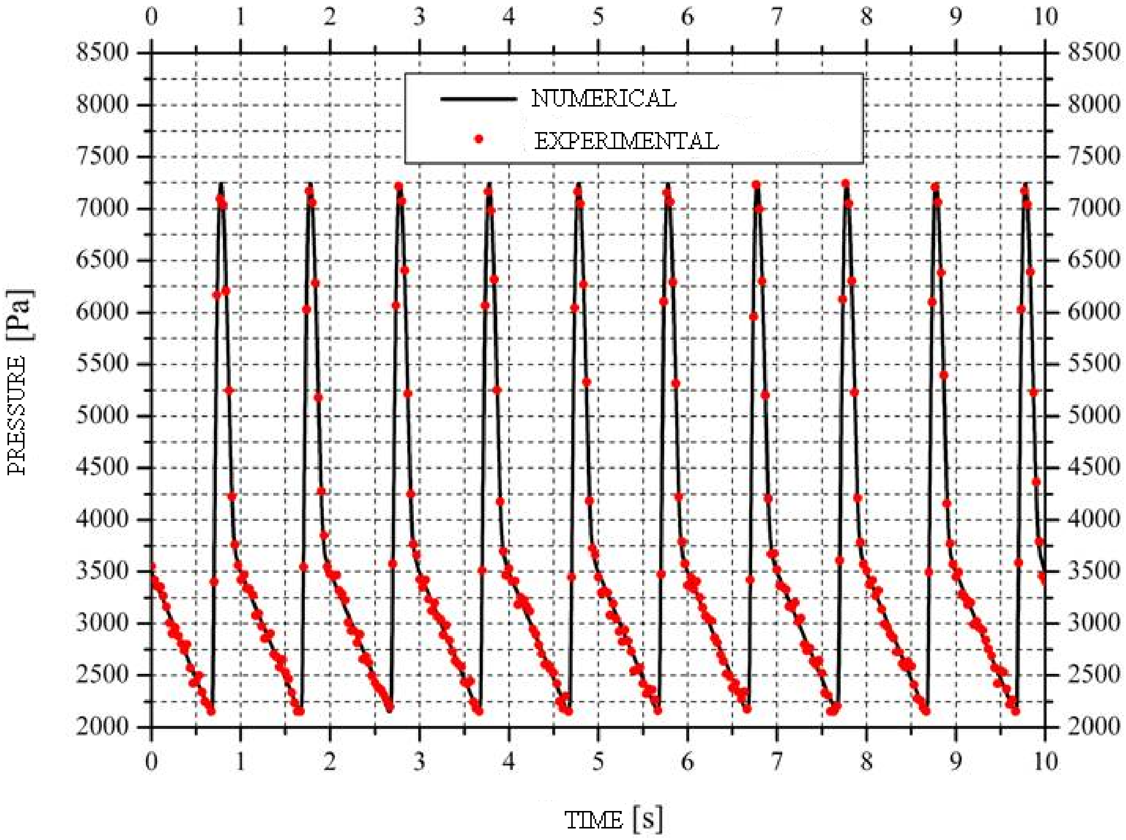

Figure 3: Comparison between the experimental and numerical pressure

Again, the results were compared between the simulated pressure and pressure treatment was excellent. Therefore, we applied the numerical model a staple of 10 mm wide, the central segment. This clip applies a force in the arterial wall can completely close the passage of blood there. The values of the clipping are arranged in two columns in Table 3.1, the first column shows the radial displacement of the rod clip, when it was compressed against the arterial wall. The second column shows the values of the forces of occlusion related to their particular shifts. The more closed is the clip; the artery is more compressed, hence the higher the value of this force.

Clipping [m]	Force [N]
0.019	0.002868
0.017	0.003028
0.015	0.003118
0.013	0.003208
0.011	0.003575
0.009	0.004252
0.007	0.0066.12
0.005	0.009715
0.004	0.013315
0.003	0.020562
0.002	0.029030
0.0008	0.43885

Table 3.1: Displacement and clipping force.

Aiming to compare the present results with experimental values, Table 3.2 presents the results of clipping developed by Machado (2010).

Clipping [m]	Force [N]
0.015	0.002825
0.010	0.003492
0.005	0.009215
0.0008	0.41750

Table 3.2: Displacement and clipping force (Machado, 2010).

Observing the behavior of forces, we noted a significant increase when it exceeds the displacement of 0.005 m. Taking as reference the arterial diameter of this simulation with the approximate value of 0.02 mm, it is concluded that from a total occlusion of the remaining quarter, the strength was 4.5 higher. The deviation between numerical and experimental results was satisfactory, with a maximum difference of about 4.8% between them.

4 CONCLUSIONS

This study sought to replicate the experiment of Machado (2010) whose pressure ranged between 54 mmHg and 16 mmHg in order to observe the behavior of radial displacement of the elastic structure. It was found that from the calibration of system, the tests validated the mathematical model. Therefore, the computational tool software ANSYS helped in the occlusion forces prediction in aneurysms clips. When the clip restricted the arterial wall, it was observed that the results of numerical simulations were quite close to the results obtained by Machado (2010). It is intended in future work to validate the numerical results with experimental results for pressures ranging between 120 mmHg and 80 mmHg, and also simulate situations in which there is hypertension. This type of simulation can be invaluable for surgeons have subsidies in the choice of appropriate clip in the surgical procedure.

REFERENCES

Ibrahim, L. B. Investigações numéricas e experimentais da mecânica dos aneurismas em tubos isotrópicos de borracha, *Dissertação* (Mestrado em Engenharia Civil) – Departamento de Engenharia Civil, Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro, 2006.

Feijó, V. Modelagem do fluxo sanguíneo na aorta abdominal utilizando interação fluido-estrutura. *Dissertação* (Mestrado em Engenharia Mecânica) - Faculdade de Engenharia, Universidade Estadual Paulista, Ilha Solteira, 2007.

Canic, S. Blood flow througt compliant vessels after endovascular repair: wall deformations induced by the discontinuous wall properties. *Computing and Visualization in Science*, Heidelberg, 5: 147-155, 2002.

Canic, S. Blood flow in compliant arteries: an effective viscoelastic reduced model, numerics and experimental validation. *Annals of Biomedical Engineering*, New York, 34: 575-592, 2006.

Wang, J.J., and Parker, K. H. Wave propagation in a model of the arterial circulation. *Journal of Biomechanics*, New York, 37: 457-470, 2004.

Ko, T. H., and Kuen, T. Numerical investigation on flow fields in partially stenosed artery with complete bypass graft: an in vitro study. *International Communications in Heat and Mass Transfer*, New York, 34: 713-727, 2007.

Machado, D. A. Construção de um arranjo experimental de simulação do escoamento sanguíneo em artérias. *Dissertação* (Mestrado em Engenharia Mecânica) - Faculdade de Engenharia, Universidade Estadual Paulista, Ilha Solteira, 2010.