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COMPUTATIONAL SIMULATION OF ABDOMINAL AORTIC ANEURISM AND ITS ASSESSMENT TO MEDICAL TREATMENT

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Abstract
Among cardiovascular diseases, aneurysms are defined as dilation of the artery or vein greater than 50% of its mean diameter. Relatively common pathology present in 9% of people over 65 years of age, aneurysm rupture mechanisms are still not identified by science. Currently, the diagnosis of when to operate an aneurysm is based on its mean diameter, as well as the physician's experience, which makes the choice between operating or not. It is estimated that 50% of people who suffer from hemorrhage due to an aneurysm die. In the evolution of the aneurysms, there is thrombus formation in which simulations can elucidate the cause and assess new treatment. The use computational tools such as fluid dynamics aid on understanding of blood flow and its interaction with artery's tissue. For the flow equation calculations, blood standard properties are modeled as viscoelastic and reofluidizing to perform the most reliable possible. Conditions that may lead to rupture of an aneurysm, such as thrombi and geometric composition, are determined in this study. It has been analyzed the structure variation that must indicate whether or not to operate an aneurysm. In this model, a methodology was developed to evaluate the fluid-tissue interaction in aneurysms in order to better elucidate the role of thrombi in the aneurysms and to propose assessment to medical treatment.

Keywords
Abdominal Aortic Aneurysm (AAA). Intraluminal Thrombi. Fluid-Tissue Interaction. Computational Fluid Dynamics (CFD). Model Specific Patient.

Introduction

One of the main causes of death in the world is cardiovascular diseases, estimates suggest that it is maintained until 2030 [1]. Mansur (2016) referred to as the first cause of death in Brazil the diseases of the circulatory system, which account for 30% of the deaths. Aneurysms are a circulatory system disorder, which is relatively common and is present in 9% of the population over 65 years of age [2]. Aneurysms are defined as dilatation of an artery or vein, which accounts for 80% of strokes [2]. The medical diagnosis of Abdominal Aortic Aneurysm (AAA) is made when there is a diameter 50% greater than the normal diameter, this criterion is important in the decision making in relation to the surgical necessity. Among the aneurysms, the most common is saccular and like other aneurysms, its cause is the defect in the middle layer of the artery; the diagnosis of this aneurysm occurs at the moment of its rupture. It is currently accepted that this aneurysm is formed by a congenital genetic anomaly and that it is due to the greater stress in the middle layer, which undergoes greater hemodynamic stress, leading to a bifurcation, which gives rise to an aneurysm [3]. There are several hereditary diseases that are the cause of the aneurysms, among them: Ehlers-Danlos syndrome, polycystic kidney, aortic narrowing, fibromuscular dysplasia, and Marfan syndrome. Other factors predisposing to aneurysms are acquired factors such as smoking, hypertension, and atherosclerosis, these being the most probable causes of an aneurysm. It is estimated that 50% of people who suffer from hemorrhage from an aneurysm die and half of those who survive have disabling sequelae [3]. AAA are classified as "true" or "false". In true aneurysms, the blood stays inside the circulatory system, but even in the false ones it passes to the neighboring tissues causing hematomas [2]. There is a great effort to obtain better criteria based on physiological phenomena in which a greater precision is sought. Among the existing resources for a better understanding of aneurysms one can highlight computational fluid dynamics (CFD), which helps in understanding diseases related to blood flow. This represents an efficient way to understand the influence of hemodynamics on medical diagnosis [4]. In order to obtain numerical solution for the system of equations, it is important to establish blood flow patterns. For this purpose, the blood without its constituents is considered as white blood cells, platelets, and red blood cells, so if we disregard these constituents we can consider it Newtonian. If these constituents are considered, the blood will have a non-Newtonian behavior, but with viscoelastic and reofluidifying characteristics [5]. McGloughlin (2011) considers that the blood can be considered as a Newtonian fluid and the muscles and walls of the arteries constituted by neo-hokeano hyperelastic materials [6]. Thus, a physical model can be developed so that its variables are studied in their limits. The greater the adequacy of the physical model to physiological factors assigning the highest number of correlations, more reliable is the model. In this work, we evaluated a patient-oriented model in which CFD simulations were performed using BioPaRR (*Biomechanics based Prediction of Aneurysm Rupture Risk - The University of Western Australia*) software. In these trials, some results were obtained in which two proposals were made for possible future treatments for aneurysms.

Experimental

Image Segmentation

The first step was to segment the image with the geometry of an aneurysm which discriminates between an aneurysm and the surrounding tissue. The tools used were free *3DSlice28* software with *3DSlicer* extensions such as *FastGrowCut*. Correlations and smoothing of label maps from which 3D structures of computed tomography of aneurysms were extracted. The region used for segmentation were below the renal arteries to the iliac bifurcation.

Intermodal Image Records

Geometric information was extracted using intermodal images, such as the wall thickness of an aneurysm. The registry makes the alignment of different images with the same coordinate system, and an image record was used, for which a label mapping algorithm was implemented. The first step was to segment the computed tomography images defined in the maps of labels. Later, the label map of the computed tomography was transformed into records for these steps are executed with *BRAINSFit* and *BRAINSResample* algorithms of *3DSlicer*, and implemented with the script programming language Python.

Wall Thickness Specification

The thickness of the artery wall distributes the stresses within the wall of an aneurysm. To perform the extraction of the artery wall it is necessary to have a good quality of computed tomography and magnetic resonance imaging being necessary both exams to extract the variable thickness of the artery. These tests depend on the resolution of the soft tissues, so constant thicknesses are often used. By using these images, it is possible to obtain thickness estimates through interpolation and smoothing, making use of ruler tools available in the *3DSlicer*. This software can read the thickness of the computed tomography walls, and when it cannot be properly performed, a constant thickness of 1.5 mm is used, which was applied in this work.

Building the Geometry

Segmented label maps of computed tomography images along with thickness are used to create geometries of the aneurysms as well as the surfaces of the internal and external walls and the surface of the intraluminal thrombus. The geometry was created in 3 (three) steps: (1) The *3DSlicer* was applied with a label manipulating the maps, the label map of the aneurysms is subtracted and the map of the aneurysm lumen is extracted the surface of the *3DSlicer* module, which results in several triangles of different sizes of bad proportions and surfaces; (2) The software *ACVDQ33-35* was used to create the mesh; (3) A *3DSlicer* module was creates the surface interface, with the module used in the previous step being reused for the separation of the aneurysm wall from the surface of the intraluminal thrombus. The internal surface of the intraluminal thrombi is then modified and a minimum thickness of 1 mm is ensured. In calculating the size of the elements, the wall thickness is generated on the size of the elements, using sizes with grid points with a spacing of 1mm and the spacing between one and the other is also 1 mm, which covers all the geometry of an aneurysm.

Computational Mesh Generation

Mesh generation is based on the intraluminal aneurysm thrombi on the surfaces of the element size configurations of the previous steps, in which it is done in three stages using *Gmsh36* free software files. In the first step, the information on the size of the generated elements and the dimensions use information from the generated surfaces. In the second step, the volumes of the thrombi of the aneurysm walls are generated and in the third, the tetrahedral volumetric mesh is created, in which size information is used. elements generated in the previous step.

Creation of the Model with the Finite Element Method

As a *CLI 3D Slicer* module it is possible to read the volumetric mesh generated in the previous step in which a file (.inp) is generated to be used in ABAQUS software, which contains the wall of an aneurysm and the intraluminal thrombi that fit the parts of the surfaces, defined the loads and automatically generated boundary conditions, which detects and includes quadratic linear configuration elements, only uses hybrid pressure and displacement formulations. There are three scenarios of analysis, the first in which an aneurysm with the thrombi have a load of blood pressure applied on the surface of the thrombi; a second scenario where aneurysms and thrombus burden and blood pressure are applied to the inner surface bypassing the thrombi; and a third scenario when an aneurysm without thrombus and with a load of blood pressure is applied to the surface of the inner wall of the aneurysms. In these three scenarios, there is uncertainty about the role of thrombi, and thrombi are believed to buffer the blood pressure in the wall, which reduces stress on the artery wall. BioPARR software has allowed us to analyze the three different scenarios.

Finite Element Analysis

The analysis of finite elements was done using commercial software ABAQUS, the simulation scenarios were those performed by the process described by Joldes *et al.* [7] in which it is possible to calculate the stress on the walls without the exact knowledge of the properties of the materials. The geometry of an aneurysm extracted from images is used, since an aneurysm with the deformation is a statically determined structure, therefore the internal stress is balanced with the forces applied externally. The load applied to the walls of the aneurysms is poor, depending on the property of the material. There are difficulties in extracting material property in aneurysms, which becomes a major advance in the biomechanics of aneurysms.

Results and Discussion

Displacement in aneurysms generates instabilities which may lead to its rupture [8]. On simulations, the greatest instability occurs when the thrombus is not taken into account, with a displacement value of $3.72\times10^{-4} \pm 2.00\times10^{-4}$ mm, followed by an aneurysm when the blood flows through the wall $5.96\times10^{-5} \pm 3.21\times10^{-5}$ mm and of the aneurysm with the thrombus with $6.10\times10^{-5} \pm 3.29\times10^{-5}$ mm. Fig. 1 presents the displacement results of simulation. This result is in accordance with the Poisson coefficient found, being the highest value when there is no thrombus, with a value of 0.486.

In these assays, thrombi increased stability by maintaining the artery more stable, but led to a weakening, which was evidenced by the Von Mises stress criterion, which is the main criterion for rupture of aneurysms [9], in which thrombi decrease the peak of tension on the wall, that is, its resistance to pressure decreases. The data found were that there were differences between the means of the Von Mises tension, being the largest without thrombus $1.27\times10^{-6} \pm 6.79\times10^{-7}$ MPa, followed by when the blood flows through the wall 5.88E-07 ± 3.17E- 07 MPa, and being the smallest when there are thrombi $5.21\times10^{-7} \pm 2.80\times10^{-7}$ MPa. Results demonstrate that in one person the thrombi decrease the tension decreasing the resistance of the person against rupture of an aneurysm. This fact is present even when there is a blood flow behind this thrombus. The literature shows that tension of 2.00×10^{-7} MPa [10] is required to maintain the integrity of an aneurysm. When analyzing the presence or absence of thrombi, over time the resistance to pressure decreases and it may lead to aneurysm rupture. The tension caused by the displacement is observed in the Poisson coefficient, the data show that there is a greater displacement in the same places of greater turbulence, which can be demonstrated skin tension of Tresca, which is related to turbulence. In the assays, the results were the highest mean values at no intraluminal thrombi of $1.37\times10^{-6} \pm 7.34\times10^{-7}$ MPa, followed by when the blood flows through the wall $6.78\times10^{-7} \pm 3.65\times10^{-7}$ MPa, followed by the lower with the intraluminal thrombi $5.89\times10^{-7} \pm 3.17\times10^{-7}$ MPa, which shows that the thrombi decrease the turbulence, which is explained by the decrease of the area where the blood circulates and modifies the blood's direction making it follow a more straight path. In addition, to the turbulence we have the Thrid tension that measures the thickness difference of the arteries and in the tests, there were no significant differences, since the thickness was constant, which collaborates with the data of the literature. Another important fact is the maximum tension that is related to the resistance force against the rupture of arteries [11].

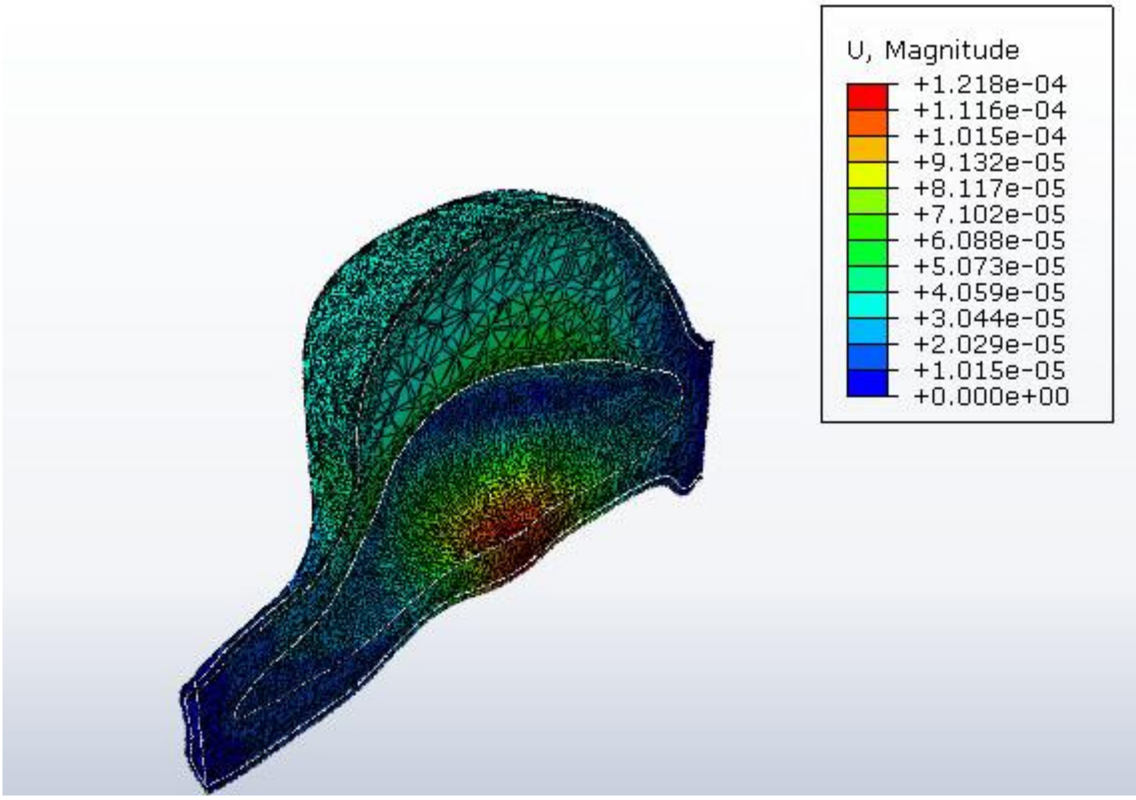

Figure 1. Displacement magnitude [mm] on the 3D geometry.

The data found were that the maximum tension without thrombus was $6.64\times10^{-7} \pm 5.00\times10^{-7}$ MPa, when blood flowing through the wall $3.62\times10^{-7} \pm 2.19\times10^{-7}$ MPa, when there is thrombus $3.16\times10^{-7} \pm 1.89\times10^{-7}$ MPa, which demonstrates that the artery has a greater force against rupture without the thrombus and when there is backflow of the thrombus, which is in agreement with the literature, since the thrombi decrease the force on the artery, with the passage of time decreases the thickness of the artery and the weaker artery, can break. The artery has greater resistance when there is no thrombus, which is also demonstrated by Young's modulus. In the simulations the greatest result was when the thrombus did not exist, with a value of 39.8×10^{-3} MPa, followed by when the blood flowed through the wall 6.40×10^{-3} MPa, being the smallest when there is thrombus with a value of 4.76×10^{-3} MPa. The maximum Young's modulus for healthy arteries varies from 3.00×10^{-3} MPa to 6.00×10^{-3} MPa [12], the thrombi make Young's modulus closer to normal, by homeostasis the body always tends to return to the balance, so he tries to return to the initial stage after undergoing pressure and the ability to return to the initial state is his resilience, which causes the organism to produce thrombi by the inflammation caused by the blow of high pressure on the walls of the arteries. This inflammation causes the body to produce pro-inflammatory interleukins that lead to blood clotting and thrombus formation. The thrombi make the arteries more stable, it helps to regain the body's homeostasis and reduces the turbulence in the vessel, but increases the risk of rupture in the long term, as evidenced by von Mises stress, increases elastic tension, causes the artery to become more rigid and with which the maximum tensile strength decreases, in a short and/or medium period of time is favorable to the organism, but in the long term, can lead to rupture of an aneurysm. Over time the absence of the thrombi leads to an increase in the tension of von Mises, and increases the elasticity with the increase of the maximum elastic tension and has a greater susceptibility to the arterial pressure variation. Since their presence has an inverse effect, it causes the artery to become more rigid and with that its resistance to maximum tension decreases, in the short and medium term thrombi appear favorable, but in the long term can lead to rigidity and elongation with large artery wall failure points, with a decrease in artery thickness at failure points, which would lead to rupture of the artery. Regarding the problem of aneurysms, two preliminary propositions are made based on the results obtained in the simulations.

The first preliminary proposition is "cement for aneurysms"
There are several types of dressings that stimulate the production of fibrous tissue, so using a bandage around an aneurysm and stimulating the production of this tissue in the regions where the artery is thinner may be interesting, since this tissue has no the same elasticity of healthy tissue, but perhaps a fibrous tissue in the artery is preferable to a very thin artery that may rupture. The arteries are believed to rupture because of their thinning, as Von Mises says, that a tension applied to the tissue with a pressure overload is not supported by the tissue.

The second preliminary proposition is a "stent with shock absorbers"
The thrombi protect the organism in the short and medium term in some way, they have been thousands of years of evolution, living organisms have a certain degree of "intelligence", it is as if they "think". The body somehow "knows" that it will not be able to make the aneurysm stop growing, and a way to protect the person to live as long as possible is a thrombus. Assuming a turbulent flow striking the wall of the artery and as it knocks it dilates, despite the flow over the arteries causing the arteries to be pressure resistant. With it getting stronger and stronger. But during the day, it is known that the blood pressure varies countless times, going up and down. Assuming a peak pressure during the day without the thrombus, the flow may hit with a very large force and may rupture an aneurysm. Since the high Reynolds number causes the pressure in this area to be greater than the center of the vessel, which has a low Reynolds, then we can infer that a pressure of 12 by 8 is amplified against the wall of an aneurysm and this amplification may rupture the same. What the body does to defend itself is to try to normalize blood flow in order to avoid pressure fluctuation and pressure on the artery wall making the thrombus. The fact is that this thrombus over time will weaken the artery and may lead to rupture, but it is less risky for the organism to break through the weakening than to be subject to constant blood pressure variations. Hypertension can worsen the picture of aneurysms leading to increased production of thrombi to protect the artery, the process of a greater impact of blood on the artery leads to an inflammatory process. The preliminary proposition from the above exposition is the possible creation of stents that can absorb the impact of blood. When the body creates a thrombus, it is to decrease the pressure on the inner wall of the artery, but this thrombus may block the blood flow in the artery. By unclogging the artery with current stents, it can lead to increased pressure on the artery, which in the short and/or medium term may lead to rupture of the artery, if it does not resist the increase in pressure, caused by the stent placement. The preliminary proposal is to make the pressure on the artery remain the same as before the placement of the stent, the preliminary preposition is in the possibility of a special type of stent, used only in people with a thinning of the artery wall that has the thrombus.

Conclusion
Aneurysms have a slow, gradual and silent progression after they are installed and when they rupture they cause bite of 80 to 90% of the cases, however when an aneurysm begins to manifest the first symptoms and if it is diagnosed in a timely manner, there is treatment, although still there is the question of knowing when to operate an aneurysm and this is due to the problematic of thrombi, there is still a lack of concordance between some groups about the thrombi. This work shows that considering the thrombi

in the computational models changes the results of the same and that the thrombi are an important physiological factor in the pathology of the aneurysms and they can protect the arteries in physiological terms, but it causes the artery to become weaker with the over time, which can lead to aneurysm rupture. This work still makes two propositions for future research, which depend on the necessary scientific tests and proofs, if the relevance of the preliminary propositions presented here is proven.

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