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Visión Electrónica

A CASE-STUDY VISION

# Modelling of the carotid artery

## *Modelamiento de la arteria carótida*

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INFORMACIÓN DEL ARTÍCULO

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ABSTRACT

This study presents a modelling for the carotid artery that allows to analyze the theoretical behavior of pressure, flow and arterial volume in it, from the variation of both physical and physiological characteristics, such as: the thickness and length of the vessel blood, the viscosity and density of blood; determinants in the study of the normal functionality of the artery. The model of the arterial vessel –an adaptation of the Windkessel model of three elements, reported by Westerhof and Stergiopulos–, consists of an electrical circuit composed of passive RLC elements. The arterial segment was analyzed by mathematical and computational tools, relating Poiseuille's laws and electric laws. The pressure, flow and volume curves were obtained when changes occurred in the measurable characteristics of the carotid artery, in order to facilitate the medical interpretation of possible pathologies related to these changes.

RESUMEN

Este estudio presenta un modelado para la arteria carótida que permite analizar el comportamiento teórico de la presión, el flujo y el volumen arterial en ella, a partir de la variación de características tanto físicas como fisiológicas tales como: el espesor y longitud del vaso sanguíneo, la viscosidad y densidad de la sangre; determinantes en el estudio de la funcionalidad normal de tal arteria. El modelo del vaso arterial, –una adaptación del modelo de Windkessel de tres elementos reportado por Westerhof y Stergiopulos–, consiste en un circuito eléctrico compuesto de elementos pasivos RLC. El segmento arterial se analizó mediante herramientas matemáticas y computacionales, relacionando las leyes de Poiseuille y las leyes eléctricas. Se obtuvieron las curvas de presión, flujo y volumen, cuando ocurrían cambios en las características medibles de la arteria carótida, con el fin de facilitar la interpretación médica de posibles patologías relacionadas con estos cambios.

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## 1. Introduction

The carotid arteries are important blood vessels, which participate in the proper functioning of the brain. There are two carotid arteries located, one on the right side of the neck (Carotid Right, CD), which is born from the brachiocephalic trunk and the other on the left side of the neck (Carotid Left, CL) that is born from the aortic arch. Each has a root called the common carotid artery (CCA), which ends up dividing into two: internal carotid artery (ACI), which supplies blood to the brain, and the external carotid artery (ACE), which supplies blood to the face and neck [1].

The wall of the carotids are composed of three layers: the intimate tunic, is the innermost layer of the carotid artery and is the one that comes into direct contact with the blood, formed by a layer of endothelial cells and lamina of internal elastin; The tunica media, works as a containment barrier preventing the pressure from breaking the vessel, it is composed mainly of smooth muscle cells with some elastin and collagen fibers, and the outermost layer of tunica adventitia, which allows to fix small lymphatic vessels and nerves, composed of collagen fibers, fibroblasts and cells associated with vascular nerves [2].

Pathologies that alter the structures and functional behavior of the carotid artery greatly compromise the functions of the brain, which is responsible for processing and regulating motor and cognitive responses in humans. These pathologies, can be, carotid artery aneurysm, carotid artery vasculitis, arteriosclerosis of the carotid artery, temporal arteritis, among others, which mostly end in a carotid stenosis, causing approximately 25% of the cases of cerebral ischemic infarcts, directly related to severe disability, dementia and even death [3].

Constantly assessing the structural and functional state of the blood vessels has become an important strategy in the prevention of strokes. For this reason, the number of studies related to the structural analysis of the carotid arteries has increased by different methods. J. S. Milner et al. in 1998, they performed a hemodynamic study and the geometry of the carotid artery, based on the three-dimensional reconstruction of magnetic resonance imaging [4]. R. Menchón et al. in 2016, they use images of the carotid artery Ultrasound to evaluate the dimensions and layers of the carotid artery, combined with a machine learning methodology to provide an early diagnostic tool in the clinical assessment of arteriosclerosis [5]. Different characteristics to the structural ones have also been taken into account. S. Z. Zhao et. in 2000, they presented a study of blood flow through the carotid and vessel mechanics in a physiologically realistic model, analyzing the movement and velocity of blood through the carotid [6]. Y. Çinar et al. in 1999, they conducted an investigation that revealed the relationship between the decrease in body temperature and the increase in blood viscosity, which in turn causes a decrease in the flow of blood through the blood vessels, and that the body, in response, generates an increase in blood pressure, which passes through the vessels, in compensation to tissue ischemia [7].

Cerebral functions are disrupted when serious alterations occur in the physiological and anatomical structure of the carotid artery, understanding the causes and effects of alterations in the passage of blood through the carotid, can be a medical alternative to prevent or treat better way these pathologies.

However, to determine the effects of pressure, flow and volume, when the parameters of density, viscosity, thickness and length are altered in the carotid artery, it is of great value in the evaluation of normal or pathological functioning of the blood vessel.

This study presents the changes in pressure, flow and volume as a result of the solution of a model analogous to the physiological behavior of the passage of blood through the carotid artery. Changes in the different anatomical and physiological variables embedded in the model and their effects on pressure, flow and volume are evaluated and are considered an important tool in the clinic, as an approach in the understanding of pathologies that affect the carotid artery and impact on facial and / or brain complications.

In the first instance, the methodology is established, the physical characteristics of the carotid artery are described and the electrical model is solved; later changes of physiological variables are made and the answers to these changes are shown in the graphs of results, these results are discussed and analyzed physiologically, finally some conclusions are established.

## 2. Methodology

### 2.1Dimensions of the Carotid Artery

A literature review of [8, 9, 10] was carried out to gather the values of the dimensions of the carotid artery (see Figure 1). In this study the CCA graphs are analyzed, and the events in ACI and ACE are inferred.

### 2.2 Model RLC Electric Circuit

The model used in this study corresponds to that published by Westerhof and Stergiopulos [11] (see Figure 2), an electrical circuit with three passive elements (resistance, capacitor and coil (RLC)), an adaptation of the Windkessel model of three elements passive. The result of this electrical circuit is a linear differential equation, an approximation to the complex physiological behavior of an arterial segment. This model has been implemented in the most important parts of the carotid artery.

**Figure 1.** Graphic representation of the right carotid artery and its dimensions in mm.

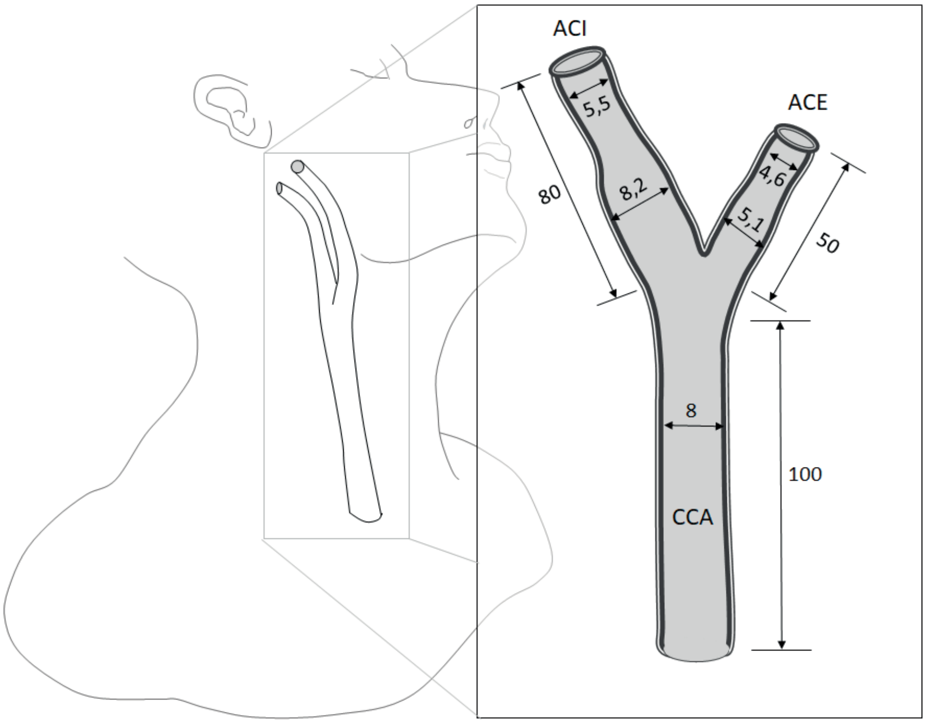

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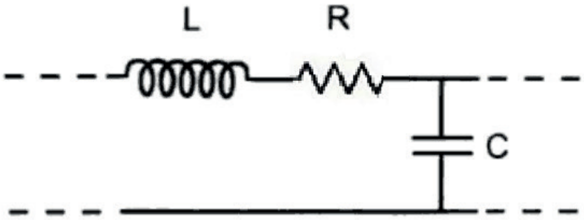
**Figure 2.** Electrical circuit as a representation of the arterial segment of carotid [11].



Additionally, the components of the electrical circuit are equivalent to physiological characteristics of the carotid artery. The resistance (R), represents the resistance of the vessel to the blood flow, the capacitor (C), is the compliance of the arterial tube and the inductance (L), the blood inertia. The application of the laws of Kirchhoff, allow to solve the proposed electric circuit. The variables and electrical temporal functions such as voltage, current and charge are equivalent to the variables and temporal functions of pressure, flow and blood volume, respectively.

The following equations relate the electrical elements with the physical characteristics of the carotid artery [11]:

$$R = \frac{8\eta l}{\pi r^4} \qquad (1)$$

$$L = \frac{\rho l}{\pi r^2} \qquad (2)$$

$$C = \frac{3l\pi r^2 (a+1)^2}{E(2a+1)} \qquad (3)$$

$$a = \frac{r}{h} \qquad (4)$$

Where $\eta$ is the viscosity of the blood, $l$ the length of the segment, $\rho$ the density of the blood, $E$ the Young's modulus of elasticity and $h$ the thickness of the wall of the artery. The electrical circuit was solved taking into account that the temporary variables and functions are equivalent between an electrical system and a hydraulic system, the solution is given in terms of pressure, flow and volume.

### *2.2.1. Solution in terms of pressure*

Solving the electrical circuit to obtain the differential equation.

$$\mathrm{P_i}(\mathrm{t}) = \mathrm{LC}\frac{d^2\mathrm{P_o}(t)}{dt^2} + \mathrm{RC}\frac{d\mathrm{P_o}(t)}{dt} + \mathrm{P_o}(t) \qquad (5)$$

Where Po(t) is the pressure as a relation between the blood volume and the distensibility of the artery and Pi(t) pressure of entrance to the arterial segment.

### *2.2.2. Solution in terms of flow*

Solving the electrical circuit to obtain the differential equation.

$$\frac{d\mathrm{P_i}(t)}{dt} = \mathrm{L}\frac{d^2\phi(t)}{dt^2} + \mathrm{R}\frac{d\phi(t)}{dt} + \frac{1}{\mathrm{C}}\phi(t) \qquad (6)$$

Where ϕ(t) represents the flow of blood through the artery.

### *2.2.3. Solution in terms of volume*

Solving the electrical circuit to obtain the differential equation.

$$\mathrm{P_i}(t) = \mathrm{L}\frac{d^2\nu(t)}{dt^2} + \mathrm{R}\frac{d\nu(t)}{dt} + \frac{1}{\mathrm{C}}\nu(t) \qquad (7)$$

Where v(t) represents the volume of blood in the artery.

## 3. Results

The graphs of pressure, flow and volume in the CCA were obtained when the values of density, thickness, length and viscosity were varied, above and below the normal or nominal value. Figure 3, Figure 4, Figure 5 and Figure 6 show the response of the model in terms of the pressure in the CCA varying the density, viscosity, thickness and length, respectively, to 60% greater than the nominal value, the nominal value and 60% less than the nominal value.

**Figure 3.** Blood pressure of the CCA varying the value of the density in the model.

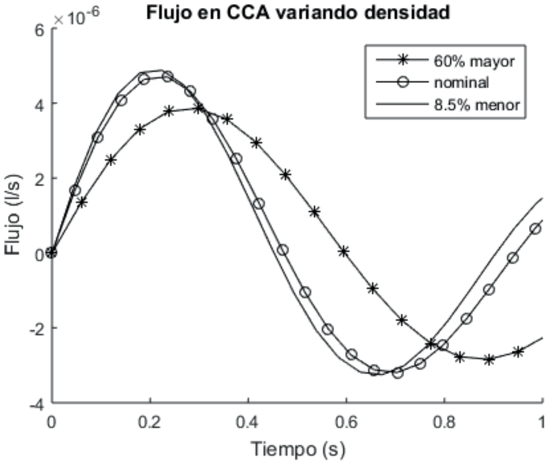


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**Figure 4.** Blood pressure of the CCA varying the value of the viscosity in the model.

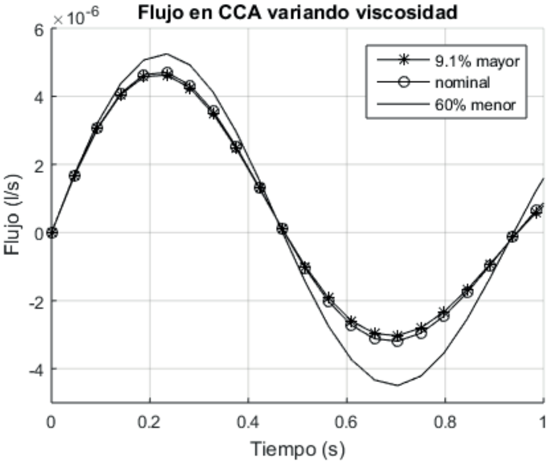

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**Figure 5.** Blood pressure of the CCA varying the value of the thickness in the model.

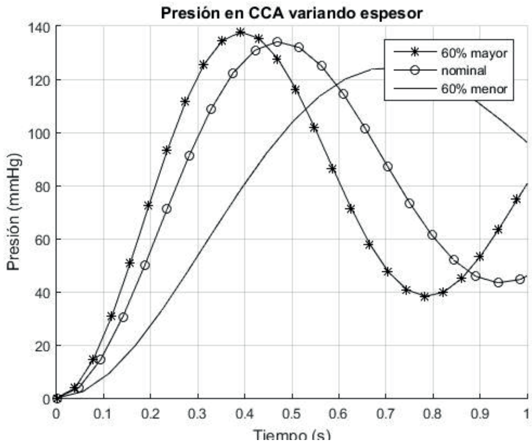

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**Figure 6.** Blood pressure of the CCA varying the value of the length in the model.

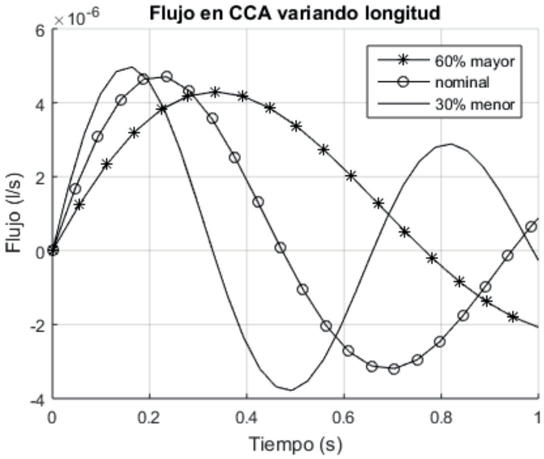

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Figure 7, Figure 8, Figure 9 and Figure 10 show the response of the model in terms of the flow in the CCA varying the density to 60% greater than the nominal value, the nominal value and to 8.5% lower than the nominal value; 9.1% viscosity greater than nominal value, nominal value and 60% lower than nominal value; thickness 60% greater than the nominal value, the nominal value and 60% lower than the nominal value, and length 60% greater than the nominal value, the nominal value and 36% lower than the nominal value.

**Figure 7.** Blood flow of the CCA varying the value of the density in the model.

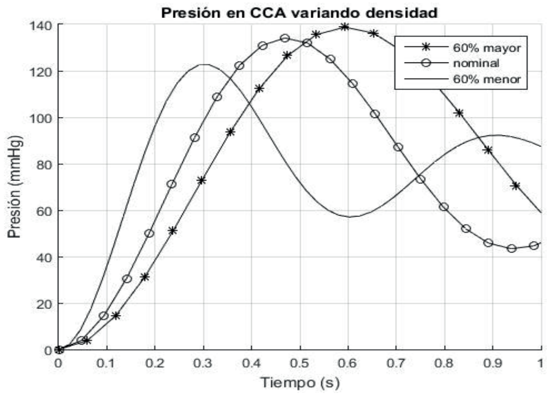

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**Figure 8.** Blood flow of the CCA varying the value of the viscosity in the model.

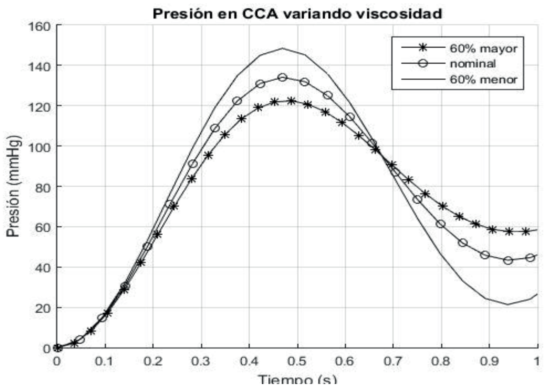

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**Figure 9.** Blood flow of the CCA varying the value of the thickness in the model.

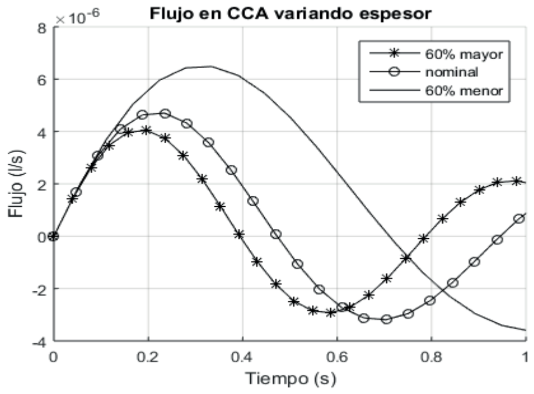

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**Figure 10.** Blood flow of the CCA varying the length value in the model.

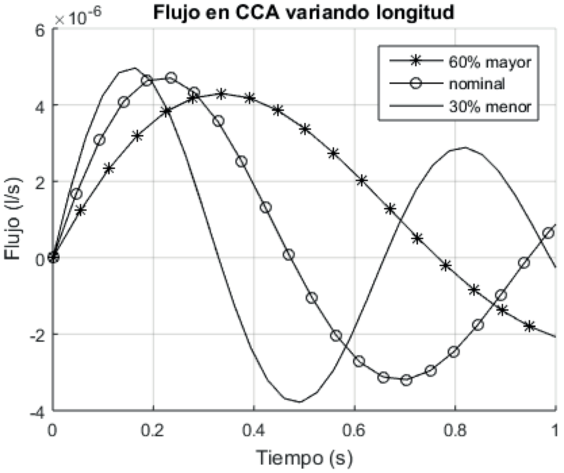

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Figure 11, Figure 12, Figure 13 and Figure 14 show the response of the model in terms of the volume in the CCA by varying the density to 60% greater than the nominal value, the nominal value and 30% lower than the nominal value; 51% viscosity greater than the nominal value, the nominal value and 60% lower than the nominal value; thickness and length, 60% greater than the nominal value, the nominal value and 60% lower than the nominal value.

**Figure 11.** Blood volume of the CCA varying the value of the density in the model.

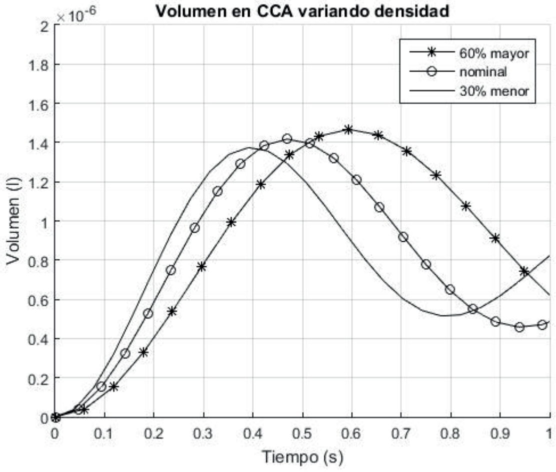

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**Figure 12.** Blood volume of the CCA varying the value of the viscosity in the model.

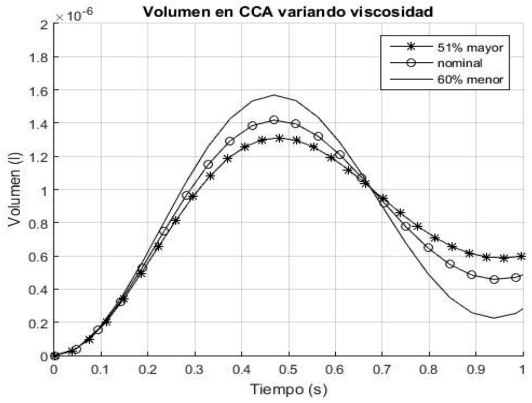

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**Figure 13.** Blood volume of the CCA varying the value of the thickness in the model.

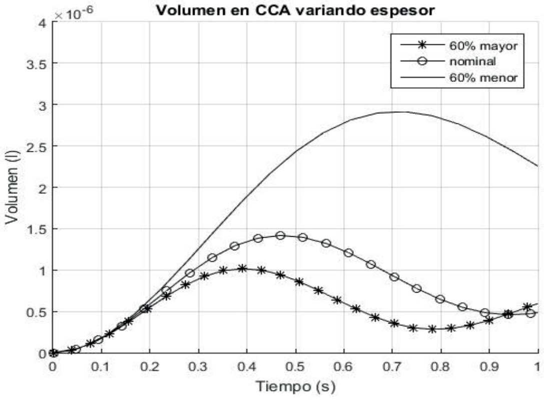

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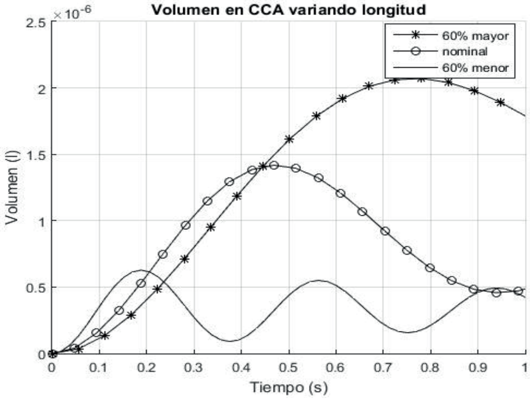
**Figure 14.** Blood volume of the CCA varying the length value in the model.



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## 4. Discussion

Different pathologies can alter the physical characteristics of the carotid artery, and these alterations cause physiological effects, which can be measured through pressure, flow and blood volume. The density of the blood is proportional to the total concentration of protein present in the blood [12], when there are high values in the level of blood density: the pressure and volume increases and the flow decreases, these results are consistent with the laws of hemodynamics; with low density values: the pressure and volume decrease and the flow presents a drastic increase.

The viscosity of the blood refers to the total friction of the cells, molecules and the lumen [13], that is, the resistance that the blood tissue presents to the blood flow, the model used presents with the increase in the viscosity of the blood. blood, a decrease in pressure (clarified, in terms of volume and distensibility of the artery), flow and volume; Y. Çinar et al, in [13], indicates in their study that, with the increase in viscosity, the pressure (in terms of the resistance of the blood to the flow) increases and the flow decreases; the data found, in this study, of flow are consistent and in terms of pressure, a complementary notion is given.

The thickness of the carotid artery can change due to the presence of inflammations of the layers of the arterial wall, as is the case of vasculitis, which can occur as a consequence of autoimmune diseases and can generate stenosis of the artery, and consequently increases the risk of cardiovascular events [14], with the increased thickness of the arterial wall, there is an increase in pressure, a decrease in blood flow and a significant decrease in the volume of blood in the artery.

The parts of the carotid (CCA, ACI and ACE) are dimensionally different, both in diameter and in length, with the ACI and ACE being shorter in relation to CCA, this implies that the pressure and flow increases, while the volume decreases, stepwise in ACI (shorter than CCA) and ACE (shorter than ACI). Possibly the bifurcation and the larger diameters at the beginning of ACI and ACE, are physiological resources for coupling changes in pressure, flow and volume in the artery.

## 5. Conclusions

On the whole, the physical characteristics are determinant to know the changes of the measurable variables of pressure, flow and volume, as clinical indicators in the evaluation of the state of a patient. These variables are mediated by several physiological factors, responses of the body to keep the biological system in balance, such as: signals from the nervous system, activation of the endocrine system, thermal compensation, etc. In this study, it was evidenced, based on an electrical circuit model, analogous to the behavior of the carotid artery, that the pressure (in terms of volume and compliance of the artery) may increase when: the blood density increases, the wall thickness increases or when the length of the artery is decreased; the flow decreases (responsible for tissue ischemia) when: the density or viscosity of the blood increases, or increase in the thickness of the wall of the artery, and finally the volume of the blood, important indicator of the amount of nutrients, proteins and vital molecules present in the blood, can decrease when: the viscosity of the blood increases, thickness of the arterial wall increases or when the length of the arterial segment decreases.

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