Nodal Analysis for Coronary Artery Ischemia Diagnosis

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Abstract. *A cardiac ischemia is a restriction of the blood flow in the heart muscle caused by narrowed heart arteries. The most common narrowing process is called atherosclerosis. The strategies to evaluate its significance are the Fractional Flow Reserve (FFR) and the Quantitative Flow Ratio (QFR) which evaluate the local impact of the atherosclerosis. This work presents a novel approach for ischemia diagnosis based on linear nodal analysis, which enables the evaluation of the whole coronary system. Even with limited variables, this method is able to indicate and quantify the impacts of a stenosis in other coronary segments than the constricted artery itself. Empirical results have shown that a left coronary artery (LCA) stenosis increases the blood flow in the left circumflex artery (LCX) together with a normal flow decrease in the left main stem (LMS), which provides secondary narrowing impact evidences. These results can complement the current techniques and increase the diagnosis assertiveness.*

1. Introduction

A cardiac ischemia is a restriction of the blood flow in the heart muscle caused by narrowed heart arteries. According to the World Health Organization (WHO), data from 2017 shows that about 31% of the deaths in the world are caused by coronary artery diseases (CAD) [Feres et al. 2017]. In the industrialized western countries, about one third of the deaths result from CAD [Guyton and Hall 2006]. CAD are usually caused by fat, cholesterol, and other substances that build up in the walls of coronary arteries, which is called atherosclerosis. Restriction of blood flow in the coronary arteries are also called stenosis.

Coronary arteries system is composed by two main arteries: the left coronary artery (LCA) and the right coronary artery (RCA). The LCA consumes around 75% of the blood flow [Guyton and Hall 2006], representing a high importance in the myocardial tissue. Hence, this research focuses in this artery in particular.

The angiography and the Fractional Flow Reserve (FFR) are described in the Brazilian Coronary Artery Guideline as the golden standard for physiology stenosis analysis [Hideo-Kajita et al. 2019, Feres et al. 2017]. Both methods are considered essential to classify the hemodynamic impact to the correct coronary artery diagnosis [Hideo-Kajita et al. 2019]. The stenosis levels can be also classified as *light* with about 50% of narrowing; *moderate* with 50-70% of narrowing; and *severe* with more than 70% of narrowing [Chakladar et al. 2017].

The most commonly adopted strategy to ischemia diagnosis is the Fractional Flow Reserve (FFR), which is an invasive approach, determine the likelihood that a stenosis will prevent tissues from receiving oxygen [Hideo-Kajita et al. 2019]. Recently, another method has emerged, called Quantitative Flow Ratio (QFR) index [Westra et al. 2018], which aims to be a less invasive diagnosis method and has been validated with FFR results. Nevertheless, both methods are invasive in some way and both use the angiography as reference. The angiography uses a catheter to achieve the lesion image and allow the operator to determine the narrowing significance according its visual anatomy.

Non-invasive methodologies have been widely used for clinical outcome of coronary artery diseases but they focused on the local evaluation of coronary blood flow reduction [Salman and Yazicioglub 2019]. Nevertheless, a stenosis affects the whole coronary system, and due to this effect, current methodologies fail to represent the whole impact of a stenosis [Salman and Yazicioglub 2019].

In this paper, we propose a new approach to determine the significance of stenosis in a coronary system. This method includes modeling the coronary system as a linear circuit and its analysis by the nodal approach, also known as tension nodes analysis [Hayt et al. 2014]. As a non-invasive step upon the coronary angiography, the present study becomes a valuable alternative to reach out similar results in comparison with the current gold standards. While the current recommended techniques are invasive and completely dependent on the operator, this research will allow the evaluation of the continuous impact of disease progression by numerical parameters changes, which can foresee the coronary blood flow blockage impact.

The role of this study is to present the preliminary results of nodal analysis applied to a modeled healthy heart. Our model is limited to a linear representation, meaning that we consider only the linear behavior of the blood flow in the coronary arteries.

The rest of this paper is organized as follows. In Sections 2 and 3, we take a closer look at the LCA physiology and common evaluations methodologies in the literature. In Section 4, we continue by introducing an approach to relate LCA segments in a mathematical model. In Section 5, we explain the basic setup of the model and how it works using some examples. Finally, in Section 6 we conclude evidencing the future work required to reach out better results.

2. Background

Coronary arteries lie on the surface of the heart, it penetrates into the cardiac muscle and are responsible for the great majority of the nutritive blood supply of the heart [Guyton and Hall 2006]. The coronary circulation is more complex than the whole body circulation, as during the systole step the blood flow is reduced by contraction myocardial muscle and then, in the diastole, the blood flow achieves its maximum [Guyton and Hall 2006]. Figure 1 presents the main coronary arteries together with the left coronary artery (LCA), which is the object of this study.

The FFR, as an invasive method with a catheter, is determined from the difference of distal pressure of the stenosis with the aorta pressure [Feres et al. 2017]. A 0.8 FFR means that only 80% of the original blood flow is achieved in the segment. An artery narrowing is significant when the FFR is lower than 0.75, and suggests the

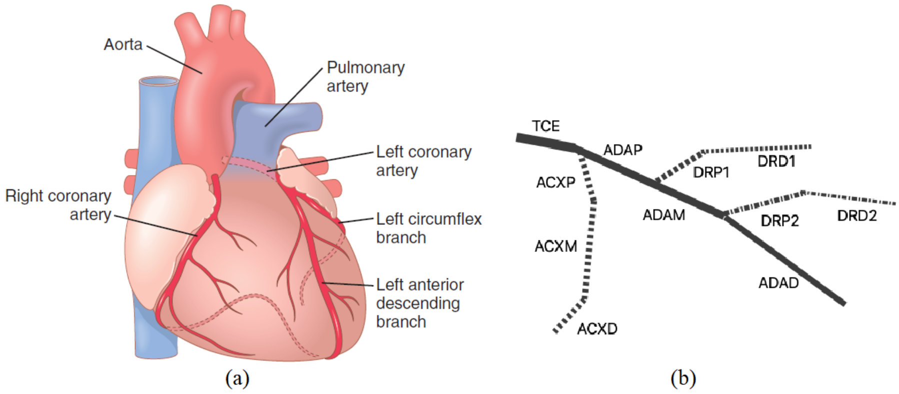

Figure 1. Coronary artery system (a) [Guyton and Hall 2006] and LCA (b).

use of a stent [Feres et al. 2017]. In general, new methodologies are validated with FFR results, as this invasive method provides quantitative information about the stenosis [Sant'anna and Brito 2009].

The QFR, as a quantitative analysis, is based on the image processing of an angiography to provide a image-based FFR evaluation [Westra et al. 2018]. This technique requires several interactions of the operator, such as: choosing two images from FFR film (these images are from two different incidences separated an angle of $25\,^{\circ}$); selecting the segment in the image to be processed; and defining the narrowing of interest. After that, the software provides a 3D-model evaluation with the fluid mechanical details of pressure in the segment [Cesar et al. 2014]. Not only QFR but even more recent studies explore the fluids mechanics concepts for coronary artery simulation and pressure estimation [Liu et al. 2020].

The local analysis of a stenosis with FFR and QFR can be helpful for the significance evaluation. However, such analyses do not consider the systematic impact of the blood flow. Some studies proposed combined solutions to improve the evidences for artery narrowing significance [Demosthenes and Ioannis 2014]. Coronary arteries physiology depends of several human characteristics and changes during their life. Nevertheless, the diameter of the left main stem (LMS) of LCA is about 4.5 mm e 3.9 mm in men and women, respectively, and these characteristics may differ in the population without any kind of atherosclerosis [Dodge and Brown 1992]. The anatomy of coronary arteries is also affected by age [Leung et al. 1991, Dodge and Brown 1992], sex [Dodge and Brown 1992, Saikrishna 2006], heart size [Macalpin et al. 1973, Leung et al. 1991], among others.

Normal coronary blood flow depends of several biological factors, but the coronary flow in rest is about 50 to 250 ml/min, corresponding about 4 to 5% of the cardiac output [Schampaert and Veer 2011, Chandran 1992, Guyton and Hall 2006]. In the same way, it is possible to get some average values of further coronary segments. Taking into account biological matters, some studies have shown that the left anterior descending artery (LAD) has an average diameter of 3.7 ± 0.4 mm, the distal left anterior descending (LADD) has an average diameter of about 1.9 ± 0.4 mm, and the left circumflex artery (LCX) has an average diameter between 3.4 ± 0.5 mm and 4.2 ± 0.6

mm [Dodge and Brown 1992]. Additionally, some studies have found that the proximal left anterior descending (LADP) has on average 3.89 mm of diameter, while the LAD has about 3.07 mm and the LADD has about 3.24 mm. On the other hand, the LCXM has about 3.16 mm, the LCXP has about 3.34 mm and the LCXD has about 2.75 mm [Zhang and Xu 2011, Dodge and Brown 1992].

Thus, considering the similarity between the values and taking into account the most complete studies, some values were selected to represent a healthy heart, and are used as the starting point of our circuit model for further nodal analysis. We selected these values especially because of the completeness of the studies and the similarity of these values among the consumed literature. Blood flow fluid mechanical and electronic concepts are widely correlated and discussed in many studies. In fact, the arterial pressure that can be represented by the voltage, the blood flow is directly associated to the electronic current, as well as the blood flow resistance can be directly linked with the resistance concepts in terms of electricity [Hassani et al. 2006, Mirzaee et al. 2009].

3. Related Work

Both Brazilian Coronary Artery Guideline golden standards, FFR and angiography approach have their limitations already explained [Demosthenes and Ioannis 2014], [Dodge and Brown 1992], so several studies and new techniques have emerged in the past few years, such as the QFR, but in general all of them have their benefits and limitations.

Each available technique for coronary stenosis analysis can be applied for a different situation. for example, also mentioned in the Brazilian Coronary Artery Guideline, the myocardial perfusion scintigraphy is applicable to evaluate if the heart is receiving blood flow in all its derivations, but it is not recommended to the quantitative evaluation of the artery narrowing [Hideo-Kajita et al. 2019]. In the other hand the coronary computed tomography angiography (CCTA) is also an expensive exam that can be used for the same purpose, but it is focused in the blood flow analysis of a local stenosis, similar to the angiography itself. In order to evaluate the main points of each study and technique, the table 1 summarize this data.

Technique	Method	LCA coverage	Flow estimation
angiography	invasive	local segment	no
FFR	invasive	local segment	no
QFR	non-invasive	local segment	no
CCTA	non-invasive	whole LCA	no
Scintigraphy	non-invasive	whole LCA	no
Proposed model	non-invasive	whole LCA	yes

Table 1. Relation between recommended stenosis analysis methods.

Techniques classified as non-invasive in the Table-1 require an initial invasive evaluation, but the technique itself is less invasive. FFR and QFR require the angiography as the reference exam for evaluation. Despite the FFR has been widely used, some studies which evaluates the long-term results of stenosis classified as significant by this method, has indicated the importance of correct hemodynamic assessment mainly for patients with stable angina, which FFR-only approach does not provide [Xaplanteris et al. 2018].

In the other hand, the CCTA, similar to the angiography also requires a contrast material to execute the image catch. Scintigraphy evaluates the presence of blood flow in the coronary arteries, but not measure or provide quantitative evaluation of coronary system blood flow. Some studies has already proposed circuit model to represent vessels and arteries [Abdolrazaghi et al. 2010, Hassani et al. 2006]. However, these studies focused in the circulatory system starting in aorta not considering the coronary system.

According to table 1 evaluation, this study presents a technique that intends to be non-invasive as the recommended methods but with more coverage than the narrowing local impact analysis focusing in the coronary system. Evaluating the blood flow quantity, this research aims to reach out more detailed information of ischemia in a holistic view.

4. Materials and Methods

This work proposes a simplified model of the LCA based on the relation between fluid mechanics and electricity. The resistance relation of fluid mechanical elements has been replaced by its lumen diameter.

Simplifying the correlation between the resistor and the lumen diameter, we took as a starting point the lowest main distal LCX segment diameter as the reference and it has been assigned as the $1k\Omega$. Then, each one of the further segments were represented as a linear resistor proportional to the referenced one. Table 2 presents the lumen diameter and the corresponding electrical resistor that we consider in this work.

Segment	**Diameter average** (mm)	**Resistor** (Ω)
LMS	4.5	1.64k
Proximal LAD (LADP)	3.89	1.41k
Medial LAD (LADM)	3.07	1.11k
Distal LAD (LADD)	3.24	1.17k
Proximal LCX (LCXP)	3.16	1.14k
Medial LCX (LCXM)	3.43	1.24k
Distal LCX (LCXD)	2.75	1k
DR1 Proximal (DR1P)	1.9	690
DR1 Distal (DR1D)	1.5	540
DR2 Proximal (DR2P)	1.7	610
DR2 Distal (DR2D)	1.4	500

Table 2. Relation between lumen diameter and electrical resistors.

Electrical resistors were disposed according to the coronary system physiology. Each resistance represents a delimited segment of LAD. The Figure 2 presents three resistors, which are respectively the LADP, LADM, and LADD segments as an electrical mesh LAD(P-D), thus enabling the use of nodal analysis.

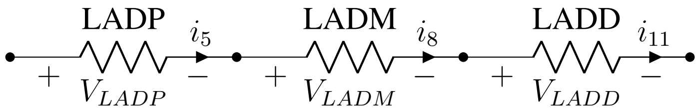

Figure 2. Representation of LAD(P-D) with electrical resistors.

Nodal analysis in a circuit model provides overall information about linear systems. Nodal analysis provides current calculations in different scenarios. A significant and a non-significant narrowing comparison presents the systemic impact of a stenosis in the coronary system. Nodal analysis was applied to the model and the same behavior is expected. This means that a higher resistance will represent a reduction in the current.

The LCA system presented in Figure 1(b) can then be linearly represented as the electrical mesh. The ground reference for the linear model has been set as the myocardial tissue, since all the blood that go through the coronary arteries end up in the myocardial tissue to guarantee the systole and diastole heart processes. The model considers that all the blood flow coming from the aorta artery, regardless where it ends up in the myocardial tissue will be introduced back to the system in the same proportion as a linear voltage source.

Due to the limited linear variables took in place, some blood flow characteristics are not ideally achieved, such as its chaotic behavior in the stenosis downstream. Also, increasing the input voltage represents the heart in a cardiac stress condition, which in a linear model will represent the same proportion between the aorta blood flow supply. However, in real cases, a non-relevant coronary stenosis in heart stable conditions, can present cardiac stress symptoms. The model presented in Figure 3 is easily built with the application of the electrical example on Figure 2 on the LCA system presented on Figure 1(b).

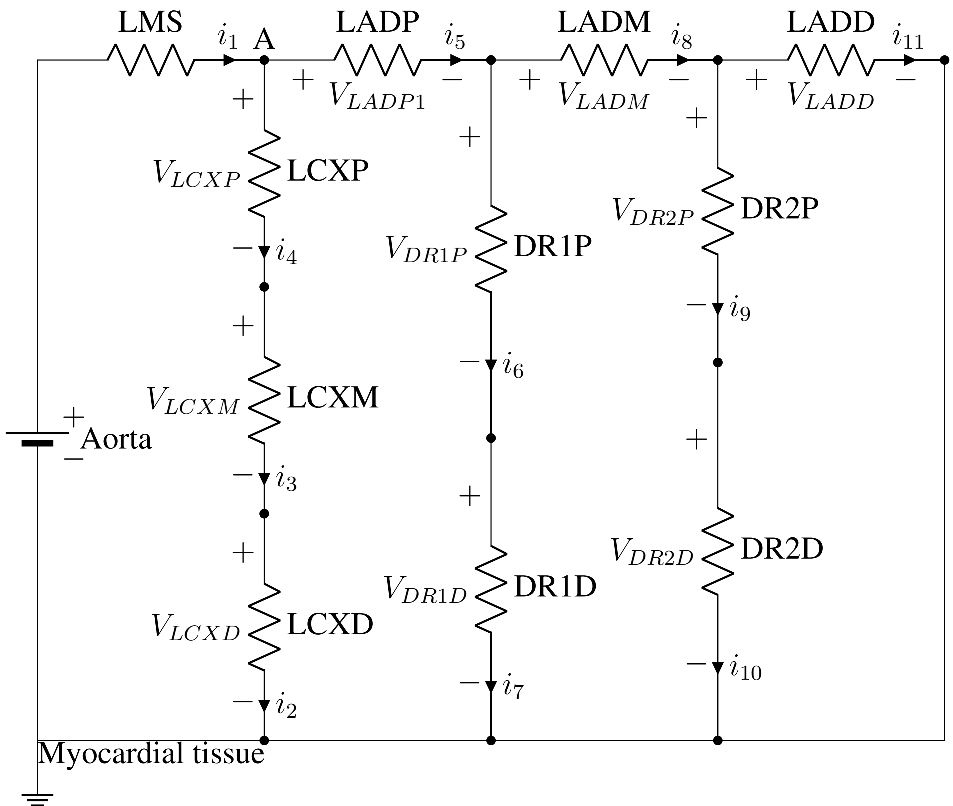

Figure 3. Proposed linear model to represent the LCA.

For the analysis purpose, we set an unitary voltage value as the input of the circuit, which makes it easier to evaluate the changes in the system's behavior. This voltage value generates a current value in each resistors representing the blood flow. Taking into account that the model represents a healthy coronary artery system, the current presented on the initial analysis indicates the healthy coronary blood flow.

For each narrowing identified in the coronary system, a new resistor is added to the model in series with the modeled one. This component addition generates a decrease in the current amount that flows through the model, thus representing an ischemia. As a flow reduction, it impacts the whole coronary system. The golden standard techniques that measure the functional impact, evaluate its local segment impact. In the other hand, the present model allows the whole system evaluation, estimating the blood flow reduction for all segments that are not considered in the significance measurement.

5. Empirical Evaluation

Considering the defined correlation between resistance and the lumen diameter together with its importance to the coronary arteries system, the LCA segment has been taken as the center study object. LCA supplies the major part of the myocardial muscle. Thus, it has been widely defined as a critical segment to evaluate the narrowing significance [Guyton and Hall 2006].

As many studies has shown, a stenosis have not only local but also a systemic impact, which is not considered by conventional methods. Increase of resistance in the blood flow circulation causes different behavior in each coronary segment. While the narrowed segment suffers from reduced blood flow, other segments suffer from increased blood pressure due to its inner pressure. As mentioned in the previous section, we have represented the LCA as a linear circuit which allows us to apply the nodal analysis technique. This technique for linear circuits takes into account the already explained conventions for electrical circuits and considers that each segment that starts in the source and ends up in the ground reference have the same voltage value.

Given a circuit model, nodal analysis is based on the interconnected dots between elements, called nodes. The aim of nodal analysis is determine the current and voltage in each element starting with a reference node. This technique is based in the concept that the sum of all the currents entering or leaving a node is equal to 0 [Hayt et al. 2014]. Following this convention, given a current value of $30\,\mathrm{mA}$ entering in the node A, and considering that the sum must be equal to 0, it is equal to the sum of $20\,\mathrm{mA}$ of LADP and $10\,\mathrm{mA}$ of LCXP. This concept is represented the Figure 4.

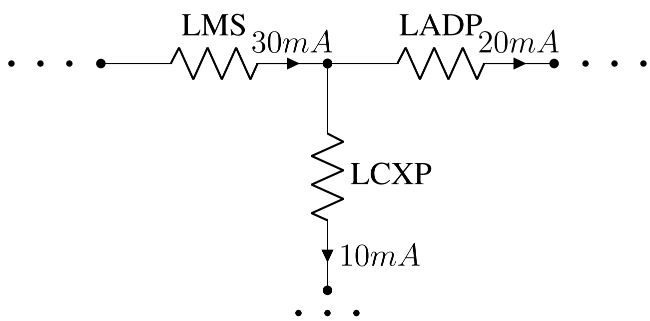

Figure 4. LMS-LADP segment blood flow convention.

In blood flow terms, all segment from the aorta to the myocardial tissue have the same pressure value. So, in case of a reduction in the blood flow in a LADP segment it will impact the whole blood flow supply in the mesh.

Considering the coronary system model, LMS has the whole current from the aorta supply, and the remaining segment from the circuit can be summed to reach the values from the aorta supply. To calculate each segment blood flow based on its resistance, the Equation 1 is used. This equation correlates the Voltage, the Resistance and the Current magnitudes.

$$Resistance(\Omega) = \frac{Voltage(V)}{Current(A)} \tag{1}$$

In order to evaluate our model, we tested four stenosis scenarios reducing LADP lumen, namely with a narrowing level of 20%, 25%, 40%, and 50% in the LADP segment, which represent 0.8FFR, 0.75FFR, 0.6FFR and 0.5FFR, respectively. These scenarios were built based on FFR results, representing each severity level of coronary stenosis [Chakladar et al. 2017]. Our objective is to show that the significance level calculation provide by our model is similar to the index obtained using FFR.

5.1. Numerical Results

The FFR ratio represents the percentage of blood flow in the segment. Table 3 shows, for the considered scenarios, that a reduction in the blood flow presents an increase of the flow in LCX(P-D), as well as a reduction in the main supply of blood in the LMS segment.

Segment	**Nor.** (uA)	**R.20%** (uA)	**R.25%** (uA)	**R.40%** (uA)	**R.50%** (uA)
LMS	340,949	327,072	323,019	309,031	297,873
LADP	209,499	188,904	182,854	162,204	145,661
LCX(P-D)	131,478	138,167	140,138	146,885	152,239
LADM	88,596	79,853	77,299	68,57	61,617
DR1(P-D)	120,984	109,038	105,554	93,633	84,136
DR2(P-D)	45,466	40,976	39,667	35,187	31,618
LADD	43,139	38,879	37,637	33,383	29,997

Table 3. Result of nodal analysis up to a 50% LCAP stenosis. stenosis.

Table 3 presents the estimation of blood flow in all coronary artery segments considering the normal LADP (Nor.(uA)) diameter together with its reduction, from 20% (R.20% (uA)) up to 50% (R.50% (uA)) of narrowing.

From Table 3, we can also notice the current value in each segment for the five determined LADP conditions. In terms of blood flow, as much as the LCA narrowing, it is possible to observe two different behaviors in other segments, increasing and also decreasing the resultant blood flow.

As can be observed in Table 3, the reduction in the blood flow of LCAP segment presents a blood flow reduction of 13%, 10%, 6.3% and 4% in the LMS segment for the 0.5, 0.6, 0.75, and 0.8 values of FFR, respectively. These results agree with FFR significance as the most significance stenosis is the one with highest resistance to the blood flow. Figure 5 shows in a visual way the quantitative difference between the test scenario results. The most different behaviors have been represented, such as the increase in the LCX(P-D) segment and the reduction in both LMS and LADP segments.

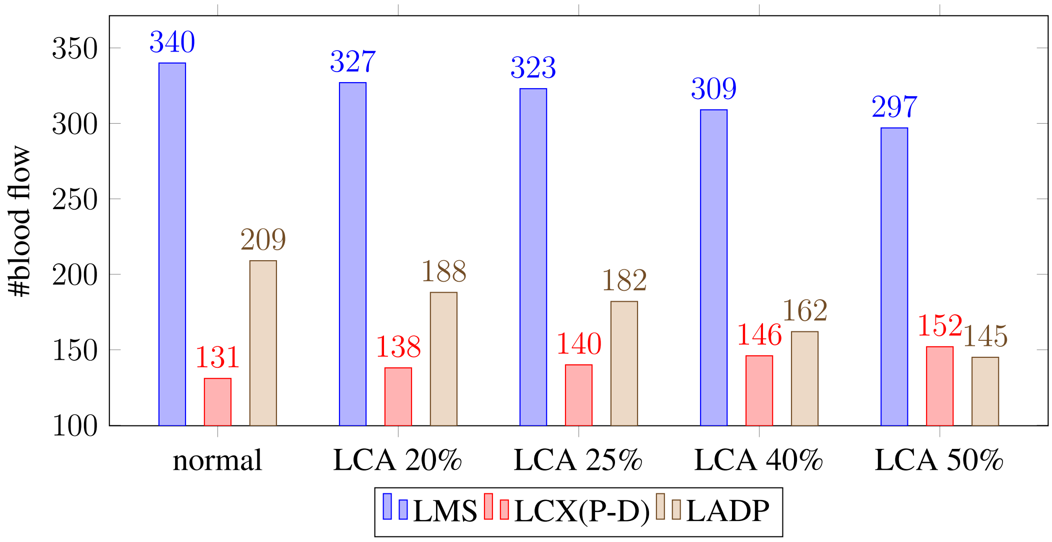

Figure 5. Comparison between nodal analysis results.

Some segments have been omitted for presenting the same behavior as some of the other segments. The DR1(P-D), DR2(P-D) and LADD segments, due to the linearity of the circuit, have the same relation between values in the five conditions. So, only the relevant behavior are present on Figure 5, presenting all LMS, LCX(P-D) and LADP segments described conditions.

Both Figure 5 and Table 3 show that a LADP stenosis increases the LCX segment's blood flow linearly in 116%, 111%, 106%, and 105% in the respective cases. These results further evidence the impact of a stenosis on the coronary system and provide some inputs about the significant and non-significant repercussions of blood flow reduction.

In fact, non-significant narrowing (when FFR values are higher than 0.75) present low impact on the inner segment, as determined by FFR. Nevertheless, a non-significant narrowing also presents an increase of 5% in the blood flow of LCX segment.

On the other hand, significant narrowing (when FFR values are lower than 0.75) present high impact on the inner segment and also a high repercussion on the coronary artery, mainly in the LCX segment. These results suggest that an intervention in the narrowed is highly recommended, not only by its anatomy, but also due to its systematic blood flow reduction.

5.2. Discussion

Given the golden standard approaches recommended by the Brazilian Coronary Artery Guideline, a coronary stenosis of 60% will be evaluated as a narrowing of approximately 60% with angiography approach and as a 0.6FFR with the FFR approach. Nevertheless, the angiography approach is subjective and its interpretation may vary from one physician to another.

Both methodologies evaluate the local impact of the stenosis and, as already explained, do not consider the systemic blood flow reduction, limiting the ischemia evaluation. These methods also heavily dependent on the operator interpretation. Even considering only the laminar behavior of blood, the gold standard methods are susceptible to significance errors, which implies in erroneous diagnosis.

6. Conclusions and Future Directions

This work presented a linear model of the coronary system based on an electric circuit to evaluate the numerical impact of a stenosis in the whole coronary system using nodal analysis.

While them are not recommended for coronary stenosis significance analysis due to its local segment evaluation, our results show that even a non-significant stenosis classified by the golden standard methodologies can cause coronary system repercussion not evaluated by them which evidence that significance requires more than just local impact evaluation. This approach is also less invasive than the conventional ones and provides data to improve the ischemia diagnosis, which is limited by the local impact of a narrowing. This is an approach for coronary artery system evaluation upon the angiography gold standard. The systemic impact of a narrowing is claimed by several authors and this research has confirmed this impact with limited variables. For sure, non-linear blood flow characteristics must be considered to reach better results and be applicable in the ischemia diagnosis.

For the future work, we look forward to consider the dynamics of the coronary system and the blood behavior. The model should be improved adding electronic components, such as inductors and capacitors to consider the dynamical blood flow condition and the arteries compliance. This will allow to study the behavior of the model with non static sources and provide more accurate data to stenosis severity. Of course, it will increase the evidence of a correct diagnosis.

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