International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056
Volume: 02 Issue: 07 | Oct-2015 www.irjet.net p-ISSN: 2395-0072

Diagnosis of arterial thrombosis and stenosis in blood vessel Using bioimpedance analysis

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Abstract: ***Bio-impedance Analysis had been used in the medical field and research with over 70 years. This technique enable a non-invasive and low-cost diagnosis of a wide range of cardiovascular pathology. It permits the access to impedance changes caused by patho-physiological processes in living tissue and allows to the diagnosis several vascular anomalies such as arterial and venous diseases (stenosis, aneuvrism and thrombosis). The objective of this paper is to evaluate the influence of an arterial constriction as a stenosis and thrombosis on the Bioimpedance signal. In order to evaluate the effects of stenosis diseases on the electrical impedance a computational fluid dynamics software (COMSOL Multiphysics) was applied. The fluid structure interaction (FSI) and Electric Currents (EC) module are used to study the effect of the changes on Young modulus which simulates atherosclerotic lesions in first step and change of stenosis severity in the second step. The study shows that increase on young modulus induce a diminution of the magnitude of the impedance signal and a supplementary oscillation in the impedance curve. The increase in stenosis severity causes a diminution of the magnitude of impedance signal but no change on the signal morphology has been detected.***

Key Words:*Bioimpedance, Pulsatile flow, Stenosis, occlusion, atherosclerosis, Numerical simulation*

1. INTRODUCTION

Cardiovascular diseases are the leading cause of death in many regions in the world. They cause more than 17 million deaths annually. There are many cardiovascular diseases involving the blood vessels, namely stenosis, aneurysm, occlusion, atherosclerosis, etc . The brachial ankle index remains the most used test in the diagnosis of cardiovascular pathologies. However, several other techniques have been elaborated such as bio-impedance analysis. The bio-impedance technique consists to measure the resistance (or impedance) change of a leaving tissue follow-up to an injected electrical current. This technique is non-invasive, promising and low-cost.

Bioinpedance deals with how to control living tissue by electricity. This technique uses electrodes to apply an external electric current and measure the potential. It allows the determination of electrical impedance of the investigated living tissue or body [1].There are a wide range of bioimpedance utilizations to estimate and evaluate the clinical states. Diagnostic usage is encountered in many kinds of conditions such as cardiac, pulmonary, renal and neural diseases [2]. Anderson had presented a review of theoretical basis and clinical applications of the bioimpedanceplethosmography in the non-invasive evaluation of peripheral arterial and venous disease [3]. Jaffrin and Morel presented a review on various bioimpedance methods to measure total body water. They compared bioimpedance analysis and bioimpedance spectroscopy methods[4]. Some of the empirical relation used and the advantages and shortcomings of these techniques had been discussed.Ward(2009) compared the performance of three commercially available bioimpedance spectroscopy analyzers in the prediction of body composition[5]. Stiles and Pettersen presented a finite element software to determine the feasibility of characterizing various types of atherosclerosis lesions in vivo[6],[7]. Mialichet al. presented a review of use of bioimpedance analysis. The application and limitation of this techniques have been discussed [8]. The bioimpedance is actually used in various clinical application and in physiological research [9]. Applications based on electrical bioimpedance (EBI) analysis have entered fields such as pulmonary system [10-11] , cardiovascular system [12], circulatory system [13-14], Renal system [15], neural system [16], Immunology system [17].

Ben Salah et al. [18] performed several investigation and research in the field of automatic diagnosis cardiovascular anomalies using bioimpedance method. They published several papers relative to the non invasive determination of arterial compliance using bioimpedance method and propose a newtechniques based on bioimpedance signal processing allowing the evaluation several hemodynamic parameters as cardiac output, stroke volume, aortic compliance, Cardiac index [19-20-21-22].

In previously study, some of the authors have developed new techniques that permit the evaluation of local mechanical properties of the artery by measuring pulse wave velocity. They also studied the effect of some pathology on this hemodynamic quantity[23]. Ben Abdessalemrecently published a book where he presented several methods of clinical interest which permit the characterization of arterial disease as stenosis and atherosclerosis [24].

The aim of this work is the Characterization of some well-known singularities such as stenosis, atherosclerosis, occlusion by the temporal measurements of bio-impedance in some reference configurations. We will deal by the characterization of stenosis and atherosclerosis pathologies by analyzing the change that can affect the bio-impedance measurements. A numerical simulation will be achieved in order to analyze more deeply the effect of these kind of disease. To the best of our knowledge, this is the first time that a fluid structure interaction with electric current module was used to study the effects of atherosclerosis and stenosis severity on the impedance signal.

2. MATERIAL AND METHOD

We intend to simulate the flow and electrical properties in blood vessel. We consider a single vessel filled with viscous fluid, of finite length '*L*=40cm' containing constriction (stenosis) at a distance x=30cm from the inlet of the tube (Figure 1). The vessel is fitted with tow electrodes in order to inject an electrical sinusoidal current with a frequency of 50 kHz. The system is governed by the Navier-Stokes equations, the equation of the motion of the vessel wall and the Maxwell equations.

Let a single pulse of fundamental frequency F_0 = 1 Hz simulating cardiac impulse, is generated at the inlet of the tube. We assume the blood density ρ = 1050 kg/m^3; cinematic viscosity η= 5 × 10^{-3}Pa s; wall thickness h = 0.3×10^{-3} m; diameter D = 3×10^{-3} m and length L = 0.4 m. let $L0$ the stenose length and l it width. We call scale of stenosis the ration :

$$S = l/L0$$

The blood conductivity is $\sigma_{blood} = 0.70\ S/m$ and it relative permittivity $\varepsilon_{r\_blood} = 5 \times 10^3$. The wall of the tube has a conductivity $\sigma_{Wall} = 0.31\ S/m$ and its relative permittivity $\varepsilon_{r\_Wall} = 1.63 \times 10^3$. the current is injected by two metallic electrodes (Steel AISI 4340) of conductivity $\sigma_e = 4.03\ S/m$ and relative permittivity$\varepsilon_{r_e} = 1$.

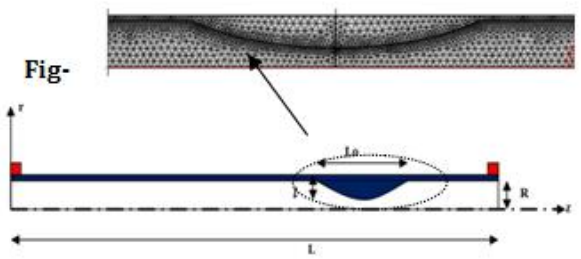


Fig-1: 1. Geometry of the arterial stenosis

All numerical simulations were carried out using COMSOL Multiphysics (COMSOL Inc) software and the analysis were carried out using MATLAB. An example of mesh used in the simulation is shown in figure 1.

Numerical simulations use a finite element method, and solve non-linear Navier-Stokes equations, and consider the fluid-structure interactions. The flow is assumed to be axisymmetric. The time dependent pressure is imposed at the inlet of the computational model (Figure 2, 3). An outlet specific condition described elsewhere (Bokov and *al.* 2013) allows imposing specific reflective or non-reflective wave conditions.Examples of input pressure (figure 2) and computed velocity (figure 3) are shown.

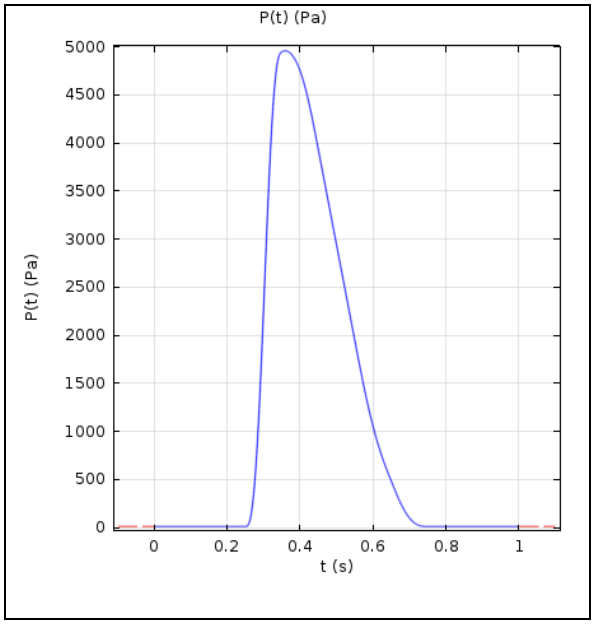


Fig- 2: Pulse pressure used in the simulation in the inlet of the tube (bottom panel)

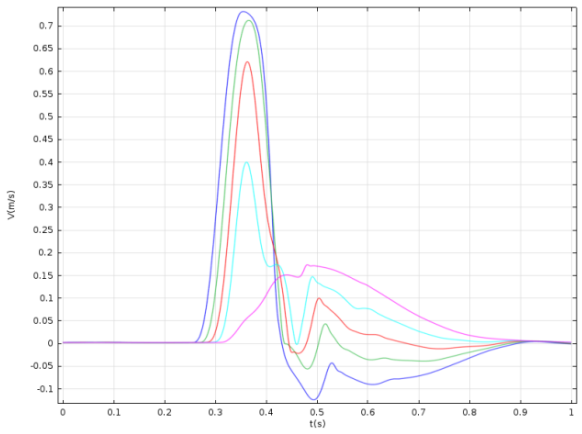


Fig-3: velocity obtained at five site of the tube.

The blood is assumed to be incompressible and Newtonian. So the Navier-Stokes equations can be written as below:

$$\rho\frac{\partial\,\vec{u}_{fluid}}{\partial t}+\rho(\vec{u}_{fluid}.\nabla)\vec{u}_{fluid}=$$

$$\nabla[pI+\mu\left(\nabla\vec{u}_{fluid}+(\nabla\vec{u}_{fluid})^{T}\right)]+\overrightarrow{F} \qquad (1)$$

$$\nabla\vec{u}_{fluid}=0 \qquad (2)$$

where ρ is the blood density, μ the Blood viscosity, $\overrightarrow{u_{fluid}}$ the blood velocity, p the pressure and $\vec{F}$ the volumetric external force

The motion of the vessel wall can be described by the following equation:

$$\rho\frac{\partial^2\vec{u}_{solid}}{\partial t^2}-\nabla\sigma=\boldsymbol{F}_V \qquad (3)$$

The electrical properties of the system are governed by the Maxwell equations in quasi-steady approximation regime:

$$\nabla.\vec{j}=Q_j \qquad (4)$$

$$\vec{j}=(\sigma+i\omega\varepsilon_0\varepsilon_r)\vec{E}+\vec{j}_e \qquad (5)$$

Where σ is the electrical conductivity and ε_r the relative permittivity ($i^2=-1$)

In the frame of the quasi-steady approximation regime, the electrical field E and the voltage V are linked by

$$\vec{E}=-\overrightarrow{grad}\,V \qquad (6)$$

The above equations will be solved using the finite element method. The ComsolMultiphysics software will be used. Then , the complex impedance will be deduced. Several geometries related to different pathologies (change in distensibility and stenosis severity) will be tested.

3. RESULTS AND DISCUSSION

Numerical simulations is performed to study the effect of varying physiological and geometrical parameters on the computation of impedance. in first step we simulate a stiffening of the arterial wall in absence of stenosis pathology. In next step we simulate the presence of stenosis with different severity. the scale of the stenosis is increased to reach S=0.9 that represent the case of occlusion.

3.1. The effect of arterial stiffness

Quantification of arterial stiffness provides an overview of cardiovascular health and determines easily patients at risk for: hypertension, arteriosclerosis (hardening of the arteries), premature aging of blood vessels and various problems which cannot be detected by the cuff. Kass et al. [25] show a relationship between arterial stiffness and ventricular function. Mitchell et al. [26] indicate that arterial stiffness is a new reliable indicator of cardiovascular disease. To simulate artery wall stiffening, we changed the value of stiffness of the wall by simulating an increase of the Young modulus (E = 0.5×10^6, 0.4×10^6, 2.5×10^6Pa). The computed impedance data is presented in Figure 4 which shows the impedance curves for six different values of Young modulus (without stenosis).

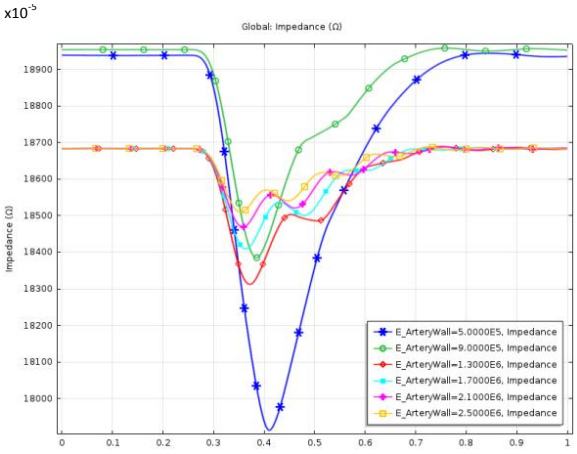


Fig-4: Electrical impedance in the absence of stenosis for several Young modulus simulating a stiffning of the artery wall.

During the cardiac activity, the arterial impedance decreases during the systolic phase and slowly takes its starting value during the diastolic phase. Simulation results confirms this impedance variation (figure 4). In addition, on note that Young's modulus induces a change in the shape of the bioimpedance signal: there is a decrease in the amplitude accompanied by a stiffening of its forehead. Level of impedance decreases by $1000x10^{-5}$ ohm for E = 5E5Pa to 200 for E = 2.5E5Pa. A displacement of the maximum to the time t = 0 is manifest.

3.2 The effect of stenosis severity

The effect of wave reflections on electrical impedance estimation seem to not be studied. In fact when approaching a singularity, for instance an arterial bifurcation, a stenosis or aneurysm, a reflection phenomenon appears. This reflected wave is due to a difference in hydrodynamic impedance between two arterial segments. This reflected wave is superimposed on the incident wave and generally induces an increase in systolic pressure. This artificial increase in systolic pressure implies extra work of the heart. Stiffer the arterial wall larger the speed of the wave reflection inducing earlier increase of systolic phase and thus of cardiac work. This change in hemodynamics conditions due to the reflected wave can affect the electrical impedance. So studding the effect of reflection on the electrical impedance seem to be of great importance. It permits the characterization of the reflection site due to the presence of a stenosis or others vascular pathology

3.2.1 Stenosis severity

Figure 5 and 6 show impedance results in the presence of stenosis with two scale (S=0.4 for Figure 4 and S=0.7 for figure 5) for several young modulus.

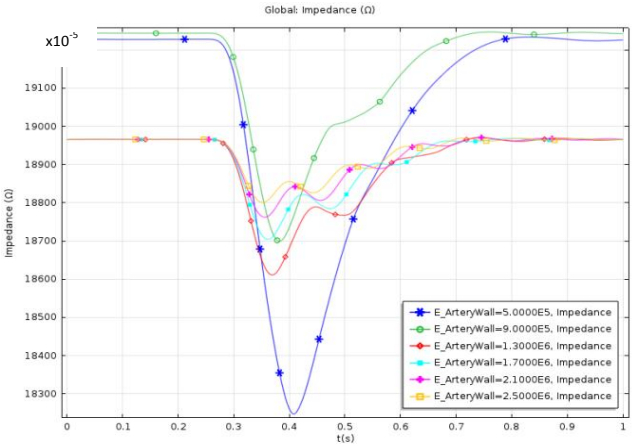


Fig-5: electrical impedance in the presence of stenosis (Scale S=0.4) for several Young modulus simulating a stiffning of the artery wall.

It may be noted that increasing the severity of the stenosis from S= 0.4 to S=0.7 induced a decrease in the magnitude of electrical impedance. However this decrease in amplitude remains low for a significant increase of stenosis severity.

Figure 5 and 6 show that the minimum of bioimpedance is displaced in the direction of time t = 0s and the electrical impedance return to its initial value Z(t=0) more quickly.

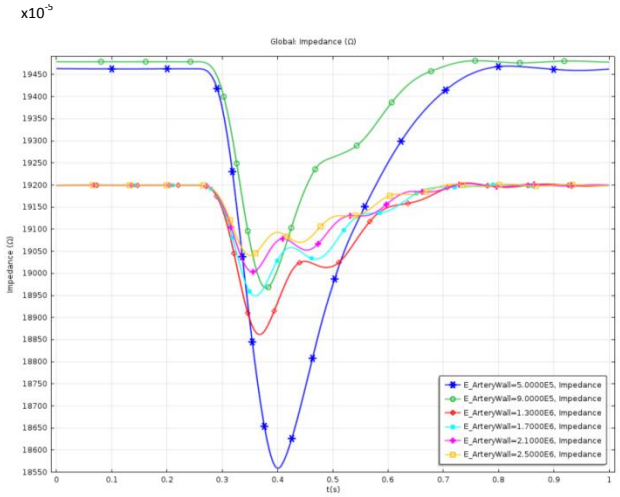
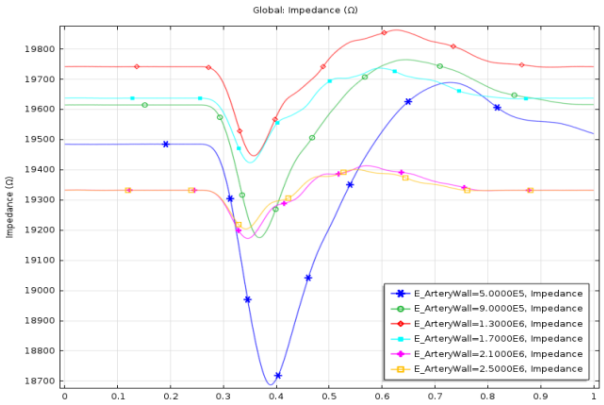


Fig-6: electrical impedance in the presence of stenosis (Scale S=0.8) for several Young modulus simulating a stiffning of the artery wall.

x10^-5 **ş- 7**: electrical impedance in the presence of stenosis (Scale S=0.9) for several Young modulus simulating a stiffning of the artery wall.



3.2.2 Effect of severe stenosis (occlusion)

Figure 7 shows electrical impedance in the presence of highely severe stenosis (Scale S = 0.9) for several Young modulus simulating a stiffning of the artery wall. A significant change in the shape of impedance signal can be seen. the impedqnce decreases during the systolic phase to reach it minimum then return quikly to it initial value. however, we can see a reversal of the concavity of the curve during the diastolic phase and the electrical impedance takes greater values than its initial value at Z(t = 0). One can also remarque a faster return (accelerate) to the initial value during the diastole.

Results found show that the decrease of the module of Young E systematically increase the amplitude of the arterial bioimpedance signal. A correlation could be envisaged between E and A. This correlation would determine the Young module of a vessel in vitro and in vivo.

In other hand Ben Salah and al. [27] have established a relationship between arterial compliance C and the maximum amplitude of the bioimpedance signal (7):

$$C = \frac{\rho . L^2 . F_M}{R_0^2 . (P_1 - P_2)} \quad (7)$$

In this formula we have:
ρ: the electrical resistivity of the blood.
L: the acquisition inter-electrode distance
F_M: the maximum amplitude of the bioimpedance signal
R_0: the basic resistance (diastolic)
P1 and P2: respectively the systolic and diastolic pressure

A relationship between arterial compliance and Young's modulus could be determined and thereby calculate Young's modulus with precision, for patients of anomalies of the cardiovascular system as well as for other pathologies such as diabetes and arteriosclerosis.

Similarly it was noted that the effect of the stenosis is to reduce the amplitude and especially the shape of the bioimpedance signal. A study more in-depth of the morphology of the bioimpedance signal by temporal processing (derived) and spectral (spectrum and cepstre) of this signal would characterize each type of signal and related it to the type of stenosis (severity).

The location of stenosis in vivo may also be considered, which requires the creation of a database drawn from the results of modelling of stenosis taking into account several parameters including: the frequency f, the d position of stenosis (distance between the center of stenosis and the entry vessel), scaling stenosis S…

4. CONCLUSION

Previously numerical investigations on the electrical impedance have concentrated on fluid flow in rigid tube. A little attention had been allowed to the effect of fluid structure integration in presence of electrical current. The results of this study show that arterial disease as stenosis an occlusion has its signature in the impedance signal. For the various stenosis severity studied the impedance signal show quantitative and qualitative dependence on the studied pathology. The lesion morphology changes the observed impedance. Using this signatures it may be characterize these pathology future in vivo.

ACKNOWLEDGEMENT

The authors would like to thank the deanship of scientific research, Majmaah University, Saudi Arabia for funding this work under project number N° 17)
The authors thank Professor HafedhBelMabrouk for simulation support.

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