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Modeling And Simulation And Imaging Of Blood Flow In The Human Body

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Abstract

Analysis of circulatory system performance is one of the most important issues in cognition, control and prevention of deformities and diseases that today are the major cause of human mortality statistics. Given the importance of the circulatory system cognition for years, many efforts have been made in identifying the system. Modeling and simulation is one of the tools that today are widely used in the service of science, particularly in the engineering field, to help the easy study of parameters and characteristics of a system. This paper presented a method for simulating an artery in a ultrasound imaging system in the Matlab environment, which easily allows the software user to determine the simulation parameters, including arterial wall thickness and diameter, number of layers in the artery and the number of existing scatterers in each layer. In this paper after the design of the artery, the wall movement pattern can be determined preferably and according to the arteries distance from heart. In this program, ultrasonic images are displayed in fixed mode in each frame and as mobile - with respect to imaging distances – as well as the signals received by the ultrasonic system.

Keywords: ultrasound simulation model, arteries, heart attack

1) Introduction

Total blood volume in an adult reached to 6 liters or 7 percent to 8 percent of body weight and flows in tubes called blood vessels. The vessels begin from the heart and end to it and carry blood to the body. Approximately there are 9600 km of blood vessels in the body which are divided into 3 main types of arteries, capillaries and veins. Arteries are vessels with thick wall that lead blood from heart to the lungs or other parts of the body. Capillaries also carry blood to all body tissues, and veins returns the unrefined oxygen free blood to the heart. In general, there are two separated blood circulation in the body; one is the overall circulation and the other is pulmonary circulation, both start from heart and end to it. One of the major issues in the field of cardiac-vascular lesions is evaluation of changes in diameter, flow velocity and elastic properties of the main arteries in the disease conditions and comparing them to the healthy state. Recently, many studies have been conducted on modeling the arteries circulation, artery walls, blood pressure and dissolved oxygen (Ahlgren, et.al, 1997; Ferrara, et.al, 1995; Gamble, et.al, 1994; Hansen, et. al, 1995). When an artery undergoes a pathological process such as atherosclerosis disease, the artery wall elasticity decreased and its firmness increases due to changes in the arterial wall (loss of elastic fibers and increase of collagen, fat deposition and increased wall thickness, etc.) caused by this disease, (Jogestrand, 1999). This paper is looking for a way to simulate arterial blood flow to present an introduction for further processing and increasing the spatial resolution of ultrasonic images. In this regard, Field II software under Matlab programming is used.

2) Problem statement

For years, coronary and carotid artery angiography has been accepted by the physicians as the dominant method for diagnosis atherosclerosis and prevention from heart and brain strokes. One of the main disadvantages of this method is its invasive effects and complications that can lead to stroke and death and also there is a risk of ionizing radiation. Angiography is incapable to evaluate arterial wall, blood flow dynamics, and detect ulcerated plaque (Baum, 1997). Hence the mechanical characterization of tissues by ultrasonic waves has attracted a lot of attention and research to diagnosis mechanical variables of vascular (Mokhtari, 2005; Peterson, 1960; Merode, 1988; Hoskins, 1998; Hayashi, 1980). Most of the studies that estimated the artery elasticity (Hayashi, 1980) and dispensability (Hansen, et.al, 1995) measured the artery diameter and its changes during a cardio period and measured the levels of brachial artery blood pressure. Despite extensive studies in the field of arterial elastic properties based on brachial artery pressure changes, definitive results have not been achieved in this field. Furthermore the available reports have not provided a method to evaluate the elastic coefficients based on the brachial artery pressure changes. Moreover, most of the methods have been designed to directly evaluate the arterial elasticity, and used brachial artery pressure instead of local pulse pressure of the artery itself. A study has evaluated the elastic variables and the stiffness of right common carotid artery based on the brachial artery pressure changes, relative changes in the cross section and relative changes in artery diameter in both healthy state and in those who suffer stenosis in the right common carotid artery, but no significant differentiation was observed (Mokhtari, et.al, 2003).

Cebral, et.al (2002) concluded that vessel wall compliance is incorporated by means of fluid-solid interaction algorithms. Boué, et.al (2007) presented a basic thermal model explaining the temperature at the surface of the skin in the presence of sources such as veins to analyse the infrared images obtained on a human forearm. Rossmann (2010) observed nonlinear and viscoelastic behavior, though most properties show little strain rate dependence. Jerez, et.al (2010) simulated the fluid-structure interaction of the aorta artery with the flux-limiter solver. Umale, et.al (2011) proposed a non-linear hyper-elastic constitutive law for the two separate liver constituents under study and their results showed that mean values of small strain and large strain elastic moduli is 0.62 ± 0.41 and 2.81 ± 2.23 MPa for veins. Wang, et.al (2012) find out strong linear correlation between the time-averaged WSS and mean blood velocity, suggesting that flow in the deep veins under the level of compression examined here can be approximated by Poiseuille's law despite local geometric variations. With the backgrounds expressed in this research, available ultrasound imaging systems use RF signals push received by the set's probe for image formation. Spatial resolution of existing equipment is in the range several times the wavelength of the ultrasound signal, which is for instance about 1 mm at a probe with 3MHz frequency. With regard to this subject, to measure vibrations with a few tens of micrometers amplitude, the RF signal processing is required. Thus in this paper to investigate the possibility of measuring low-amplitude vibrations of coronary arterial wall, a model is presented for RF signals extraction.

Many other researchers have done research on the use of robots in medical science, including: Hosseini, Khamesee (2009), Hosseini, Khamesee (2009, IEEE), Hosseini, Mehrtash, Khamesee (2011).

3) Research method

Mathematical modeling in Matlab software environment is used for modeling the experimental environment. The Field II software package is also used in modeling which has been developed by Jørgen Arendt Jensen in Denmark University of Technology (Jensen & Svendsen, 1992). Different types of ultrasonic transmitters and receivers and their related images can be simulated by this software. Focus and Apodization of transmitter - receiver can be controlled dynamically and therefore different types of ultrasound imaging systems can be simulated in this environment. Also in this environment, the wave velocity and pulse repetition interval is under user control, and two separate arrays with different specifications can be defined for the transmitter and receiver, however, as it is desired to design an environment close to real conditions, only one array is defined as a receiver - transmitter. Responses are received both as single element respond and the total element respond. This respond can be stored or displayed in different forms. In this study a receiver - transmitter array is used with the specifications provided in Table 1. Elements used for the analysis are presented in Table (2).

Table 1: Specifications of receiver - transmitter array

Parameters	quantity
Wave velocity	1600 m/s
Wave frequency	7.50E+06
Sampling frequency	1.20E+08
Excitation function	$\sin\left(2\pi f_0\left(0:\frac{1}{f_s}:\frac{2}{f_0}\right)\right)$
Frequency Response	$\sin\left(2\pi f_0\left(0:\frac{1}{f_s}:\frac{2}{f_0}\right)\right) \times max(size\{impulse - responde\})$
Array type	linear Array
Focus point	70 mm

Table 2: Specifications of receiver –transmitter elements

Parameters	quantity
Number of elements	82
Length of elements	5 mm
Width of elements	2 mm
Distance of elements	0.1 mm
Number of scan lines	200

By Field II program, the studied receiver – transmitter can be viewed. Shape and spatial position of Field II software environment array enable users to consider the parameters of ultrasonic wave attenuation in the tissue by the help of "set field" command. In the simulations of this study, this parameter was ignored to ease the receiving of returned pulses.

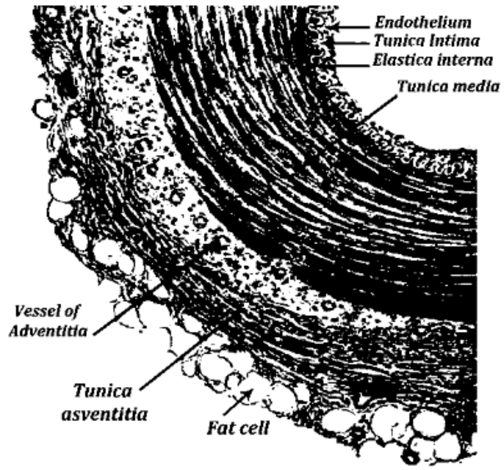
4) Model presentation

When the environment and send - receive system of ultrasonic wave was simulated, a model for simulation of the studied artery should be obtained. In the design, a cylinder with radius, the wall thickness, the number of layers and the desired compaction of scatterer with random distribution in each layer were used for simulation of healthy arteries. Image formation is in ultrasonic imaging systems based on ultrasonic beam reflected from the boundary of two layers with different acoustic impedance or scatterers available in the environment (Wong et al, 1993). The simulation in study used to model the phenomenon, many scatterers were used and these scatterers are randomly placed in the artery wall and their number varies in different layers of the wall. Based on the actual arterial pattern, the studied artery is divided into three main layers, although the number of layers in the arterial wall is more than three layers, the nature of these layers is often identical and the only major difference is obvious in the three main layers called Endothelium, Tunica media and Tunica Adventitia. Therefore in this research the three main layers are studied, thus parameters related to arterial simulation are as presented in Table 3.

Table 3: Profile of simulated arterial

Parameters		quantity
External radius		7.5 mm
Inner radius		6.1 mm
Artery length		8 mm
Layer thickness	The first layer	0.25 mm
	The second layer	0.75 mm
	The third layer	0.4 mm

The number of spots in the simulated artery is the symbol of muscle cells in the real arterial wall. Distribution density of points in the third layer which is the outermost layer, because of fat tissue and capillaries in this layer, is considered less than the other two layers. The density difference is a good parameter to distinct between the Intima layer and Adventitia layer which can be seen in Figure 1 (Fawcett, 1986). But in reality these two layers are not separable from by the help of ultrasonic images. Figure (2) shows the simulated artery with the specifications in Table (1 and 2) and due to small differences in the number of spots in the three layers and the way they are displayed, the three layers are not distinguishable by eye.



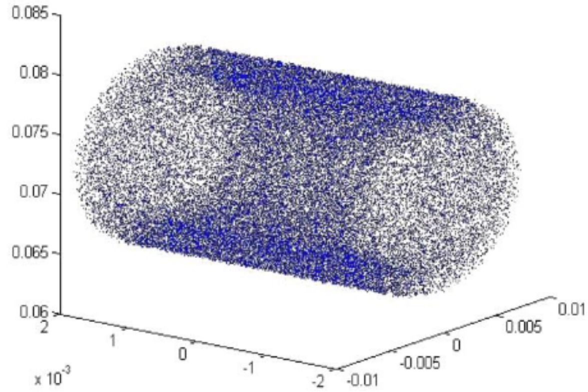


Figure 1: Three main layers of the artery **Figure 2: simulated artery**

Scatterers' movement at a heart beat follows a periodic function. However, it is assumed that due to the fact that during systole the artery wall diameter reduces and at the same time the radius of the artery is increasing, displacement level of the scatterers reduces by increasing distance from the center of the artery. For artery movement in a heartbeat, the motion models available in the reference (Hasegawa et al, 2004) are modeled. As shown in Figure 3 the wall displacement fluctuation level at the QRS wave time is more than displacement changes at the T wave time, i.e. at the T-wave time the wall movement follows an approximately linear uniform model. Thus, the wall motion is displayed in 79 consecutive frames with imaging intervals proportional to chart changes during a beat - the interval between two consecutive frames during the QRS wave is much less than the time interval between two consecutive frames during the T wave distance to the beginning of the next beat.

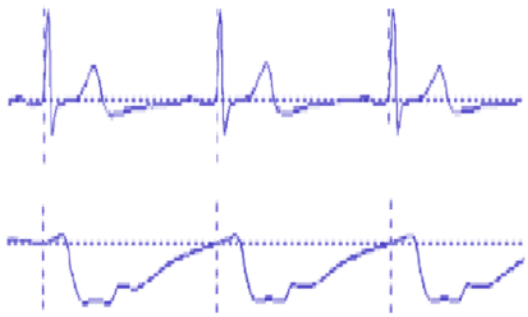


Figure 3: The pattern of heartbeat

Wall vibrations that are the major factor for diagnosis diseases such as atherosclerosis have been simulated both in random in three x, y, z directions or only in the radial direction with a different initial phase. Since in this model the imaging is only for at specific times, these vibrations with small amplitude and large fluctuations frequency at the mentioned times are added to the walls big movement. In this model to simulate arterial hardening disease, given that the hard parts are usually made by fibrous and calcium tissues which are in the hard tissues group, this part of the wall tissue only has a large overall motion in radial direction due to the heartbeat and there is no change of wall thickness and vibration in this section of wall. Thus in the obtained mages this part of the tissue distinct from other parts and by processing signals received from such a motion, the disease can be diagnosed even at initial steps in which only the inner wall layers have begun to hardening. Figure (4) shows signals received by each of the recipient elements from the mentioned artery separately and also for ease of viewing the enlarged image, a part of the artery is also shown. The following images are the responses of artery simulation program at the end of the diastole. These images are able to be stored for two-dimensional processing.

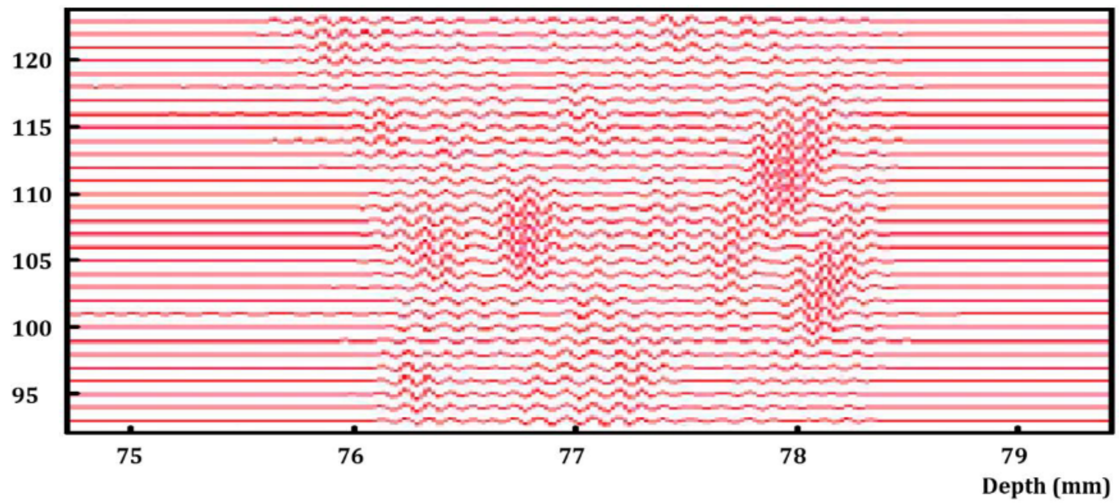


Figure 4: Results of the arterial simulation and enlargement of a part of the wall

5) Conclusion

In some of the articles in the field of ultrasonic signal processing, there are some simulations to prove the initial hypothesis of the article. One of these articles cited in this paper is (Watanebe et al, 2002) in which a model is used for the arteries in the C programming environment, but has not mentioned the effective parameters in modeling. By this program the ultrasonic images are displayed in fixed mode in each frame and mobile - with respect to imaging distances - and also the signals received by the ultrasonic system. Subsequent attempts should study the received signals in successive frames of the secondary process to examine the arterial hardening disease in its early stages through extracting parameters from RF ultrasound signals.

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