Mathematical Modeling of Common Carotid Artery Using Polynomial Interpolation by Automated Lumen Segmentation and Estimation of Numerical Attributes

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***Abstract*— Computational models of arteries in the cardiovascular system provide insight into normal and diseased conditions in blood vessels and have applications in areas such as surgical planning and medical device design. Aortic elasticity and stiffness has been proven to be a strong independent predictor of cardio vascular diseases (CVDs). Many features have been used to quantify arterial elasticity and stiffness. This paper describes a novel and automated technique for segmentation and boundary detection of the lumen of common carotid artery (CCA) using longitudinal B-mode ultrasound images. Numerical attributes are measured from the detected boundary of lumen. The main objective of this work is to develop mathematical model of CCA to describe its behavior during a cardiac cycle and determine good arterial features based on the attributes to characterize the elasticity and stiffness of CCA. Attributes are measured for each frame and analyzed for minimum two cardiac cycles to see the changes from systole to diastole. Polynomials that describe the diameter of CCA as a function of cardiac cycle time are derived from the attributes using different interpolation methods. Findings of this analysis would be very useful for the diagnosis of abnormalities in the CCA.**

***Index Terms*—** Carotid artery, ultrasound, segmentation, measurement, mathematical modeling.

I. Introduction

Cardiovascular disease is the first leading cause of death and adult disability in the industrial world [1]. World Health Organization revealed in a recent study that by 2015 almost 20 million people will die from cardiovascular diseases, mainly from stroke and heart diseases. An estimated 17.3 million people died from CVDs in 2008, representing 30% of all global deaths. Of these deaths, an estimated 7.3 million were due to coronary heart disease and 6.2 million were due to stroke. By 2030, almost 23.6 million people will die from CVDs, mostly from heart disease and stroke.

Arteries are blood vessels that carry blood between the heart, different tissues and organs of the body. They have ability to expand or contract to allow more blood or control the flow. Hollow centre through which blood flows is called lumen. CCA supplies blood to skull, brain, eyeballs, ears and external nose. When the blood supply to parts of the brain is suddenly interrupted, stroke occurs [2], [3].The diameter of CCA decreases due to increase in the thickness of arterial wall due to plaque deposit. This causes a reduction of the lumen with possible vascular problems and alters the arterial properties elasticity and stiffness. The intima-media thickness (IMT) of the CCA is widely used as an early indicator of cardiovascular diseases. It is usually measured by using ultrasound imaging [4], [5].

As the carotid artery supplies oxygenated blood to the brain, it may be very useful to quantify its stiffness information in the early diagnosis and characterization of vascular diseases such as carotid artery atherosclerosis [6]. The intimal thickening of stenotic artery is known as a beginning step of atherosclerosis. Atherosclerosis is a common dangerous disease and a major cause of death in many countries. There are a large number of investigations which have led to the understanding of the flow disorders due to stenosis [7], [8]. Advanced medical treatment of atherosclerosis is one of the challenges for contemporary medicine. A study of vascular diseases and, in particular, of atherosclerosis impact on haemodynamics may be based on mathematical models and numerical simulation [9].

Blood flow induces body forces and stresses in the arterial walls due to complex fluid–structure interactions. These forces and stresses play an important role in the onset and progression of many acquired and congenital cardiovascular diseases such as atherosclerosis and aneurysms. Atherosclerosis involves the accumulation of plaque in the intima of the arterial wall, which reduces arterial lumen and increases local arterial stiffness [10], [11]. Moreover, the mechanical quantities stress and strain are known to trigger the onset of several diseases such as atherosclerosis. These facts are some of the reasons why the mechanical properties of arterial wall tissues have received increasing attention in the literature over the past few years [12], [13].

Arterial properties estimated from the ultrasound images can be used to assess arterial stiffness and atherosclerosis in the study of CVDs [14], [15]. As ultrasound imaging allows noninvasive assessment of the degrees of stenosis and plaque morphology, it is widely used in the diagnosis of atherosclerosis of the carotid artery [16]. Ultrasound experts with insufficient experience may not often draw useful conclusions from the images due to the speckle noise. The application of edge detection and segmentation algorithms is also limited by speckle noise [17], [18]. Segmentation of atherosclerotic carotid plaque in ultrasound imaging is investigated in several studies [19]. For the segmentation of the carotid arteries, several algorithms have been proposed in ultrasound imaging. But, an algorithm that performs the segmentation based on minimal user interaction is important in the research context.

The current advances in computational modeling and numerical simulation techniques, together with the increasing computational power offered by personal computers, have allowed researchers to study, develop and solve highly accurate mathematical models which are capable of giving insight about the physical phenomena taking place in complex physiological systems, such as the Human Cardiovascular System. Although an extensive effort has been devoted so far, there are still a series of open problems of great relevance and clinical impact [20].

As an early indicator of CVD, we are also interested in the segmentation and characterization of CCA. In the previous work boundary of CCA was extracted using watershed and wavelet transforms. The diameter was measured from the extracted boundary and used for the analysis of plaque deposit in the vessel [21], [22]. In this work an effort is made to segment the lumen, measure the properties of CCA to analyze the changes in arterial properties during a cardiac cycle and develop mathematical model capable of representing the diameter of CCA as a polynomial function of cardiac cycle time using interpolation methods.

II. METHODS

A. Image Acquisition and Database

The arterial movements are recorded in the Ultrasound machine Prosound Alpha-10 from Aloka. ProSound Alpha 10 introduces the "Ultimate Compound Technology", setting a new standard in diagnostic ultrasound. The probe used is a multi-frequency probe of range 5-10 MHz. For this application the frequency is set at 7.5 MHz, since the CCA is at a optimum distance from the skin. The video is recorded for 2 to 3 cardiac cycles of carotid artery in B-mode at a rate of 29 frames per second. The blood pressure of the patient is also checked and recorded as the changes in arterial stiffness are accelerated in hypertension.

B. Automated lumen segmentation

Boundary of lumen of the carotid artery is segmented and detected by performing the following steps using AphelionTM imaging software suite which is an image processing and image analysis software. First the color image is converted to gray image.

1) Filtering: A smoothing filter is normally used to compensate for excessive image noise. Here, a Gaussian filter is used. Gaussian filters are rationally symmetric in two dimensions. The smoothing effect reduces the impact of noise in the image but also alters the position of the object boundaries for increased σ. For this case, the value of σ is chosen as 5 so that the boundary is not altered much. The Gaussian function is given by Equation 1.

$$G_\sigma(x,y)=\frac{1}{2\pi\sigma^2}\quad \exp\left(\frac{-\left(x^2+y^2\right)}{2\sigma^2}\right) \tag{1}$$

σ – Standard deviation

2) Segmentation of Lumen: Thresholding technique is used to segment the boundary of lumen. Global thresholding is the simplest and most widely used of all possible segmentation methods. This simple algorithm works well in situations where there is reasonably clear valley between the modes of the histogram related to objects and background. To extract the objects from the background, threshold value T is selected first. Then any point (x, y) in the image at which f (x, y) > T is called an object point. Otherwise the point is called background point. The segmented image g (x, y) is given by

$$g(x, y)= \begin{cases} 1 & \text{if } f(x, y) > T \\ 0 & \text{if } f(x, y) < T \end{cases}$$

As lumen area is dark; threshold segmentation is performed to identify the dark objects having pixel values in the range of 0 to 80 for this case. Figure 1 shows the filtered and segmented image.

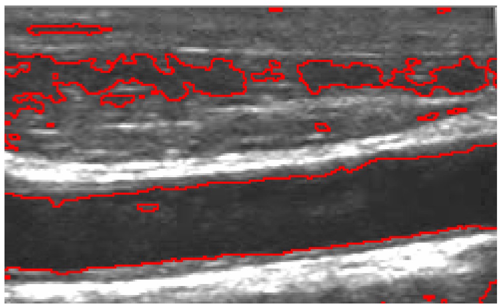

Fig. 1. Filtered and segmented image

3) Hole filling: Generally, holes are either part of the object or an image artifact that obscure or alter that part of the object in the image. It is found by inspecting Fig. 1 that small holes are inside the boundary of lumen and they are removed by doing hole filling process. The effect of this process is shown in the Fig. 2. Now the boundary of lumen is well separated and detected from other objects as shown in Fig. 3

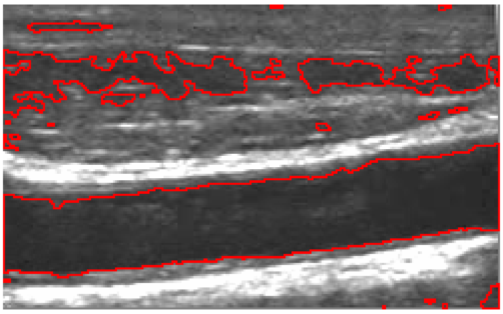

Fig. 2. Removal of holes present inside the boundary

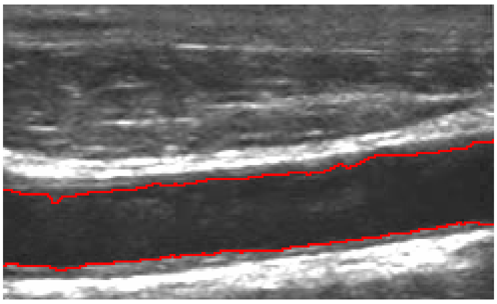

Fig. 3. Boundary of lumen of CCA

III. MEASUREMENT OF ATTRIBUTES

Distension is an important elastic property of an artery. It is the change in diameter of artery from diastole to systole which is equal to one cardiac cycle. Systole refers to contraction of blood vessel and diastole to relaxation. To analyse the elastic property and to characterize the carotid artery, numerical attributes of segmented lumen are measured from the detected boundary for each frame using Aphelion™ imaging software suite. Numerical attributes are measurable and scalar values describe some aspect of an image or segmented object. The following four attributes of lumen are measured in this work to quantify the diameter and distension of CCA.

Area is the first attribute and it gives the value of area of lumen which is inside the boundary. The second one is equivalent diameter that gives the diameter of the circle whose area is equal to the area of the lumen. The third attribute elongation is the absolute value of the difference between the inertias of the major and one minor axis, divided by the sum of these inertias of the boundary. The minor axis is defined as the perpendicular axis to the major axis. This measure is zero for a circle and approaches one for a long and narrow ellipse. It gives details related to the shape of the boundary of lumen. Pixel count is another attribute that gives the number of pixels comprising the lumen. These four attributes are directly related to the changes in the lumen and diameter of the carotid artery.

Video of CCA of a healthy subject with a length of 5 second is converted into images at the rate of 25 frames per second and the proposed segmentation algorithm is applied on 50 images obtained from the video and boundary of lumen is detected. As the normal cardiac cycle time is 0.8 second and it varies in between 0.75 to 1 second, 50 images are sufficient to analyse the arterial properties in two cardiac cycles.

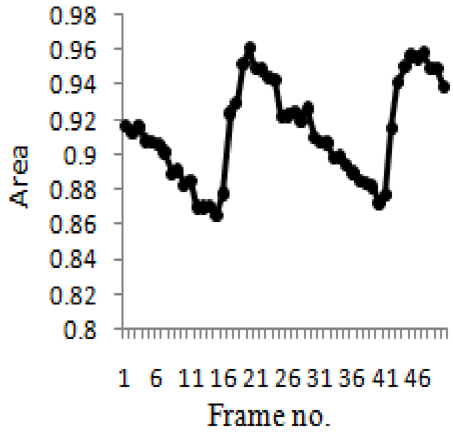

Fig. 4. Changes in the lumen area

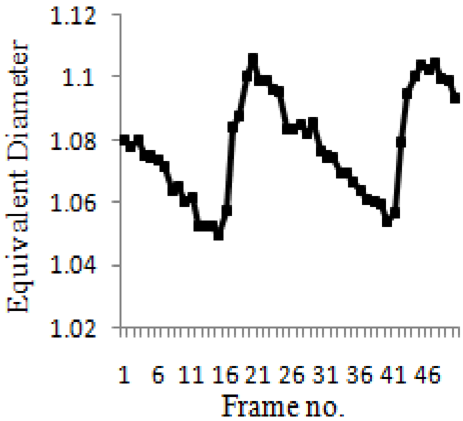

Fig. 5. Variation in equivalent diameter of lumen

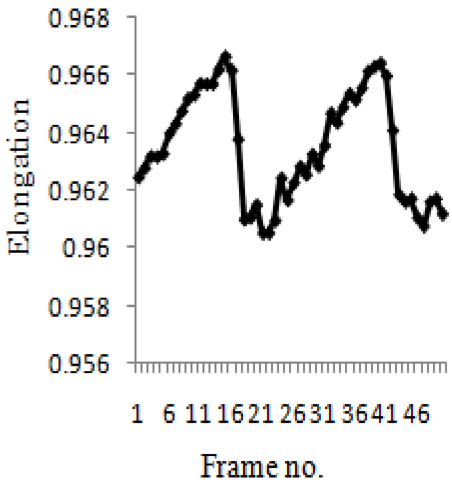

Fig. 6. Elongation showing changes in the lumen shape

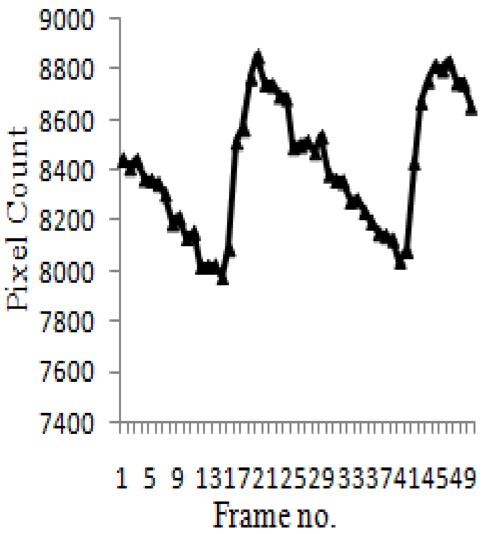

Fig. 7. Variation in number of pixels in the lumen

From the detected boundary, numerical attributes like area, equivalent diameter, elongation and pixel count are measured for all 50 images. Variation of these attributes with respect to the frame number is plotted and analyzed. Fig. 4 shows the variation in the lumen area within the detected boundary in scaled units for more than two cardiac cycles. Variation of equivalent diameter and elongation in scaled units are shown in the Fig. 5 and 6 respectively. Change in the number of pixels comprising lumen is given in the Fig. 7.

By analysing the variations in the values of attributes measured from the detected boundary of lumen for two cardiac cycles, it is found that all the four attributes increase and decrease between the peak and valley points. This is due to the fact that CCA contracts during systole and expands or relaxes during diastole. Systole takes one third of cardiac cycle time whereas diastole takes two third. This statement is true only for ventricular systole and diastole and it is reverse for atria. The atrial systole takes two third of cardiac cycle time and atrial diastole takes one third. Because the cardiac cycle only focuses on events occurring in the ventricles and always atria and ventricles go through separate cycles of systole and diastole.

This fact is observed in all the plots by taking the number of frames from valley to peak and from peak to valley into consideration. During the expansion or relaxation of CCA, the values of area, equivalent diameter and pixel count except elongation are increasing and number of frames is less which is approximately equal to one third of total frames in a cardiac cycle. During contraction, the values are decreasing and number of frames is more which is approximately equal to two third of total frames in a cardiac cycle. For elongation, the values are increasing during contraction as the shape of lumen approaches long narrow ellipse and decreasing during expansion of CCA.

IV. Mathematical Modeling

From the plots, it is clear that the values of measured attributes increase and decrease with respect to frame number which can also be represented as cardiac cycle time. As 25 frames are taken for a second, time between two successive frames is 0.04 seconds. All the plots show the variations of attributes for a random period of 0 to 2 seconds. If a polynomial is derived from the known values of attributes, it is possible to estimate the missing as well as future data. Hence, a mathematical model is developed to derive a polynomial for equivalent diameter of CCA as a function of cardiac cycle time. Though the frames are taken only for particular time intervals, equivalent diameter at any time can be computed using the derived polynomial.

Interpolation is the process of computing intermediate values of a function from a given set of values of the function. Extrapolation is the process of finding the values outside the interval. But in general, the word interpolation is used in both processes. There are various methods of finding such interpolating polynomials. In this work, three methods are used to construct polynomials. If $y = f(x)$ denotes a function which takes the values $y_0, y_1, \ldots y_n$ corresponding to the values $x_0, x_1, \ldots x_n$ respectively of x, then interpolation is given by the following three methods.

A. *Newton's forward interpolation formula*

The forward interpolation formulae of Newton can be used only when the values of independent variable x are equally spaced. Formula is given by Equation 2.

$$P_n(x)=P_n(x_0+uh)=y_0+\frac{u^{(1)}}{1!}\Delta y_0+\frac{u^{(2)}}{2!}\Delta^2 y_0+\ldots+\frac{u^{(r)}}{r!}\Delta^r y_0+\ldots+\frac{u^{(n)}}{n!}\Delta^n y_0. \quad (2)$$

$$\mathbf{u}=\frac{x-x_0}{h}.$$

h – Time interval

B. *Newton's divided difference formula*

This formula is given in Equation 3 and this is used in case of unequal intervals.

$$P_n(x)=f(x_0)+(x-x_0)f(x_0,x_1)+(x-x_0)(x-x_1)f(x_0,x_1,x_2)+\cdots+(x-x_0)(x-x_1)\cdots(x-x_{n-1})f(x_0,x_1,\cdots x_n) \quad (3)$$

C. *Lagrange's interpolation formula*

In case, where the values of independent variable are not equally spaced and incases when the differences of dependent variable are not small, ultimately, Lagrange's interpolation formula given by Equation 4 is used.

$$y = P_n(x) = \frac{(x-x_1)(x-x_2)\cdots(x-x_n)}{(x_0-x_1)(x_0-x_2)\cdots(x_0-x_n)}.y_0 + \frac{(x-x_0)(x-x_2)\cdots(x-x_n)}{(x_1-x_0)(x_1-x_2)\cdots(x_1-x_n)}.y_0 + \cdots + \frac{(x-x_0)(x-x_1)\cdots(x-x_{i-1})(x-x_{i+1})\cdots(x-x_n)}{(x_i-x_0)(x_i-x_1)\cdots(x_i-x_{i-1})(x_i-x_{i+1})\cdots(x_i-x_n)}.y_i + \cdots + \frac{(x-x_0)(x-x_1)\cdots(x-x_{n-1})}{(x_n-x_0)(x_n-x_1)\cdots(x_n-x_{n-1})}.y_n \quad (4)$$

V. Results

The peak and valley points are identified from the plots and the minimum and maximum values of variation in the attributes are given in Table I.

TABLE I. NUMERICAL ATTRIBUTES MEASURED FROM THE DETECTED BOUNDARY OF LUMEN OF CCA

Attribute	Max Value	Min Value	Variation
Area	0.96	0.86	0.1
Equivalent Diameter	1.11	1.05	0.06
Elongation	0.967	0.961	0.006
Pixel count	8855	8021	834

The variations in the attributes given in the Table I are for a healthy subject and they can be used to classify the normal and abnormal CCA. Measurement results clearly show that the numerical attributes obtained from the detected boundary of lumen are highly related to distension of CCA.

Three data sets with equal and unequal intervals are taken from the measured values of equivalent diameter (ED) for the construction of polynomials. Table II shows the data sets.

TABLE II. DATA SETS FOR CONSTRUCTING POLYNOMIALS

Set I		Set II		Set III	
Time (t)	*ED (d)*	*Time (t)*	*ED (d)*	*Time (t)*	*ED (d)*
0.4 s	1.0601	0.2 s	1.0748	0.6 s	1.0499
0.8 s	1.1060	0.6 s	1.0499	0.8 s	1.1060
1.2 s	1.0764	0.8 s	1.1060	1.2 s	1.0764
1.6 s	1.0541	1.2 s	1.0764	1.6 s	1.0541

Set I consists of 1 peak, 1 valley and 2 intermediate points with equal intervals. Set II also has 1 peak, 1 valley and 2 intermediate points, but with unequal intervals. There is 1 peak, 2 valley points and 1 intermediate point with unequal intervals in set III. The peak and valley points are included to ensure the complete behaviour of CCA in one cardiac cycle.

Polynomials are obtained by applying the interpolation methods. As set I is with equal intervals, Newton's forward interpolation is applied by considering x = t and y = d = f (t). Polynomial for set I is obtained as given in equation 5.

$$d = f(t) = 0.2156t^3 - 0.7533t^2 + 0.7773t + 0.8564 \quad (5)$$

Similarly Lagrange's Interpolation and Newton's divided difference formula are applied for set II and III respectively as they have unequal intervals. Polynomial for set II and set III is given by equation 6 and 7.

$$d = f(t) = -1.162t^3 + 2.4362t^2 - 1.4014t + 1.2674 \quad (6)$$

$$d = f(t) = 0.6136t^3 - 2.1862t^2 + 2.4329t + 0.2446 \quad (7)$$

Polynomial curves generated for set I ,II, and III are given in Fig. 8, Fig. 9 and Fig .10 respectively.

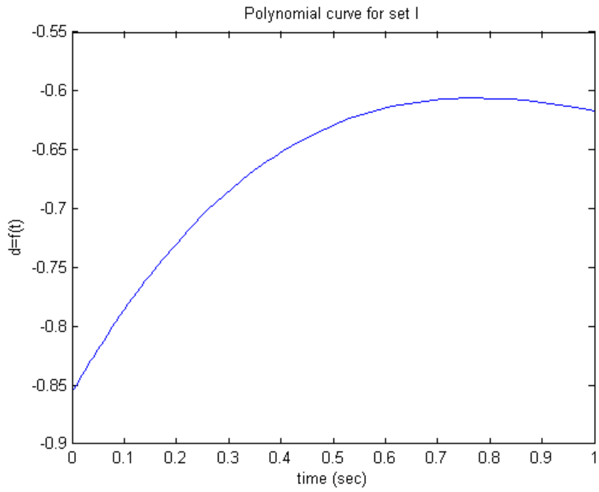

Fig. 8. Polynomial curve for set I

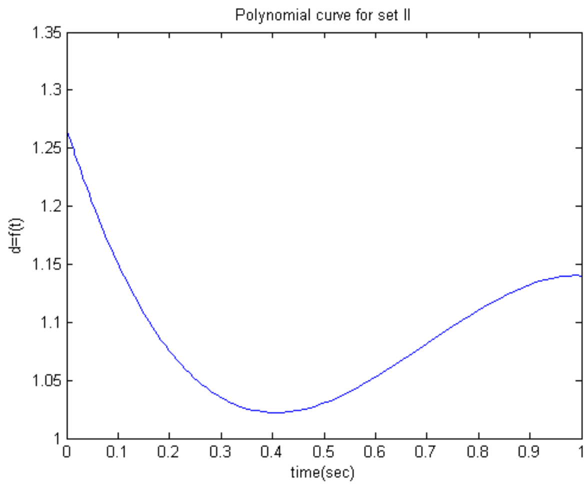

Fig. 9. Polynomial curve for set II

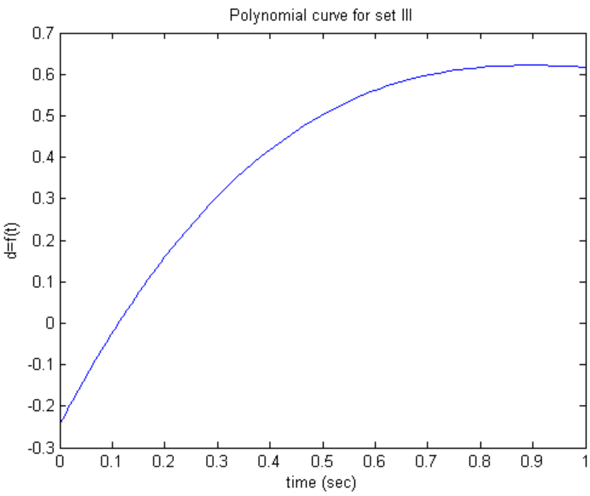

Fig. 10. Polynomial curve for set III

By comparing the actual curve in Fig. 5 and traced polynomial curves, it is clear that the curve traced by set II matches with the actual curve. The curves traced by set I and III do not follow the pattern of actual curve. Values in the y axis lie in the same range of actual values for set II curve and deviates for set I and III. Error between the exact curve and the interpolating curve is minimum for set II polynomial than the polynomials of set I and III. Same observations are found in Table III which gives the variation in measured and computed values of equivalent diameter for different time. Further the error can be minimized by taking more data points to construct the polynomial.

TABLE III. TABLE III COMPARISION OF MEASUERED AND COMPUTED VALUES OF EQUIVALENT DIAMETER (D)

Time	**Measured Value**	**Computed value**		
		Set I	***Set II***	***Set III***
0.2 s	1.0748	0.9834	1.0752	0.6499
0.6 s	1.0499	1.0982	1.0526	1.0498
1.0 s	1.0834	1.096	1.1402	1.1049
1.4 s	1.0699	1.0597	0.8918	1.0494
1.2 s	1.0935	1.1226	1.0866	1.2744

VI. CONCLUSION

A method is proposed to create mathematical model and characterize the elasticity and stiffness of common carotid artery with good arterial features by detecting the boundary of lumen and measuring the numerical attributes using longitudinal B-mode ultrasound images. The boundary of lumen is segmented and detected by applying thresholding technique. From the detected boundary, numerical attributes area, equivalent diameter, elongation and pixel count are measured and plotted for 50 images obtained from a healthy subject. The variations in the values of the attributes are observed for more than two cardiac cycles. It is found that the variations follow the behavior of common carotid artery during systole and diastole. The measured attributes have excellent correlation with distension and these can be used to quantify the elasticity and stiffness of CCA. Variation of attributes between the peak and valley points can be used as an indicator to detect arterial stiffness since the variation is directly proportional to elasticity and indirectly proportional to stiffness.

From the measured values, a mathematical model is created to describe the changes in equivalent diameter with respect to cardiac cycle time using polynomial interpolation. Three data sets are taken and polynomials are derived based on different interpolation methods. Same polynomial functions are obtained when different interpolations are applied for a data set. Polynomials completely depend on the data points. Out of three polynomial traced curves, one match with actual because of the chosen data set. If the values are chosen in such a way that they describe the complete behavior of CCA in one cardiac cycle, then the error is minimized. Polynomial constructed with minimal error can be used to compute the value of equivalent diameter for any given time interval and to analyze the changes in the diameter that can be correlated to the elasticity and stiffness. Hence the proposed mathematical model can be used to develop a decision support system for analysing the abnormalities in the CCA.

Risk factors such as cholesterol, blood pressure, smoking and diabetics correlate to the arterial stiffness and CVDs. If the measurements are related to these risk factors, it would be very useful for the prevention of CVDs. Future work will focus on further testing of the proposed method in a larger image dataset considering all these risk factors to validate the good features to develop mathematical models for detecting abnormalities in the common carotid artery and classify the healthy and unhealthy subjects.

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