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Sparse models and recursive computations for determining arterial dynamics

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ABSTRACT

Arteries expand and contract in every cardiac cycle. Arteries of a healthy individual are elastic. Increased arterial stiffness is an established marker of the vascular health. An estimate of this vascular stiffness may be obtained by measuring the diameter of the Common Carotid Artery (CCA) in each cardiac cycle. This is typically done using image based systems.

ARTSENS[1] is a portable, image free, ultrasound device for evaluating the stiffness of the CCA. ARTSENS emits a sequence of ultrasound pulses and records the reflected echoes. These echoes are then used to identify the CCA and estimate its diameter, and thereby evaluate the arterial stiffness. This paper deals with development of algorithms for determining the echoes due to the CCA and the estimation of its diameter.

Here, the propagation path of each ultrasound pulse is modeled as an FIR filter considering the Gaussian modulated sine (GMS) pulse as the input and its reflections from the walls of the artery and other anatomical structures as the output. The impulse response of the FIR filter is sparse as its output has only few significant echoes. The echoes are reconstructed using the estimated filter coefficients and observed that the reconstructed signal is noise free. This results in the reliable tracking of the artery walls and evaluating its lumen (inner) diameter.

The filter coefficients (impulse response) are first determined using Matching Pursuit (MP) algorithms. Additionally, the MP algorithms are made recursive to enable online filtering of the data. The inner diameter of the CCA was calculated for twenty seven subjects using the reconstructed (filtered) data. The estimated diameters were compared with diameters obtained from a B-mode imaging system and was found to be in close match. Furthermore, it is found that for a subject, only the non-zero impulse responses and their sample numbers need to be stored to recover the filtered echoes. Leading to a significant data compression.

1. Introduction

Coronary arteries (CoA) supply pure blood (oxygen-rich blood) from the aorta (largest artery that supplies oxygenated blood to the entire body) to the heart muscles. The inner walls of CoA are lined by a thin layer of endothelial cells. These cells preserve the CoA flexible and toned for a smooth flow of blood. Endothelial cells get damaged due to aging, high blood pressure and high cholesterol levels. Damage to the endothelial layer results in the accumulation of degenerative materials such as calcium, lipids, fat and other cellular waste on the inner walls of the artery, thereby narrowing the arterial diameter (lumen, see, Fig. 1) and stiffening the arterial walls. This occludes the blood flow and diminishes the supply of oxygen and nutrients to the heart muscle causing a Coronary Heart Disease (CHD). Measurement of the arterial stiffness can be used to predict the CHD, [1]. Lumen diameter (along with systolic and diastolic blood pressure) reveals the stiffness β[2] of the coronary arteries, [2,3]. Coronary arteries are not available to non-invasive diagnostic tools (such as ultrasound), [4]. It has been noted that stiffness of the Common Carotid Artery (CCA) is a good indicator of the CHD, [5]. CCA runs along the neck region and supplies pure blood to the brain. And significantly, it is accessible for non-invasive diagnos-

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[1] ARTSENS was developed in Healthcare Technology Innovation Centre.

[2] $\beta = \frac{\log \frac{p_s}{p_d}}{\frac{D_s - D_d}{D_d}}$, where p_s, p_d are the systolic and diastolic blood preassure respectively,D_s and D_d are the systolic and diastolic diameteres of the artery.

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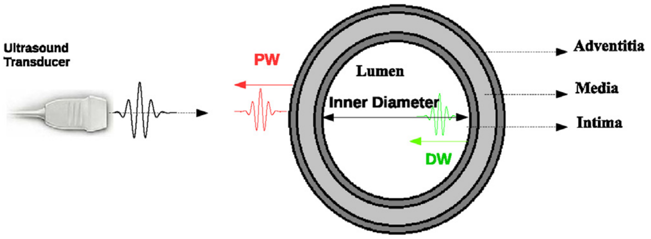

Fig. 1. Layers of CCA.

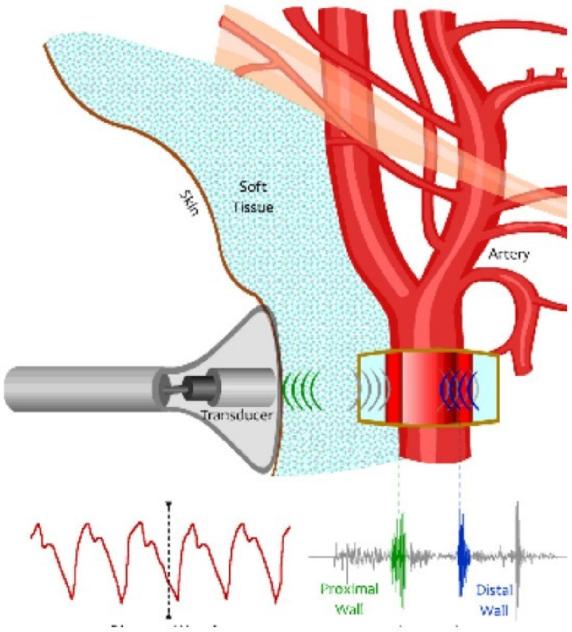

Fig. 2. Data acquisition.

tics. This paper deals with the estimation of the lumen diameter of the CCA.

ARTSENS is an image free non-invasive hand held device that can be used for determining the stiffness of the CCA, [6,7]. The main purpose of ARTSENS is to screen large scale populations for early detection and prevention of cardio vascular diseases, [8]. When screening large scale populations the device used must be easily usable by a non-expert operator, portable and must provide results in very short time. Commercially available instruments for measuring CCA stiffness (such as Aloka e-tracking system) are expensive and require a licensed sonographer for operation, [9,10]. The complexity of the computations involved in generating the images and estimation of the arterial diameter from the ultrasound data (Radio Frequency ultrasound signals) makes their usage difficult when screening large populations. Furthermore, imaging systems are subject to the rules and regulations of the countries in use (for example, Preconception and Prenatal diagnostic techniques act (India)) due to their association with fetal sex determination and abortion. Their use is limited to licensed practitioners. While ARTSENS being image free and portable with automated algorithms for wall detection, tracking and stiffness measurements makes it amenable for health care workers to perform quick vascular health evaluation in field. This enables for early detection of at-risk subjects for timely intervention.

The carotid Initima Media Thickness (IMT), aortic Pulse Wave Velocity (PWV) and CCA stiffness are established measurements for evaluating vascular health and risk, [11,12]. IMT measurements need a high fidelity imaging system [11,12] and a trained operator. Clinically relevant aortic PWV estimation requires measurement of carotid-femoral PWV [11,12], which is impractical in large scale screening. In many social contexts measurement of carotid-femoral PWV could be a very sensitive issue. However, CCA stiffness measurements could be performed either using ultrasound imaging systems or image free systems [13,14].

Most literature on measuring these indicators can be slotted into two classes, the ones using B-Mode images to measure the indicators, [9,15–18], and the others using Radio Frequency ultrasound signals (RF Signals) directly acquired from the ultrasound sensors (without generating an image), [13,14]. In many cases, the IMT and the lumen diameter of the CCA are estimated with manual intervention, [19,20]. B-Mode systems allow for marking the Intima, Media and Adventitia, see Fig. 1, manually on the images. The IMT and Lumen diameter are estimated by determining the distance between the marked points. In [15] an automated scheme without manual intervention is presented for determining the IMT. This method, based on edge detection schemes, though robust cannot be used for large scale screening due to the use of B-Mode imaging system and the computational complexities involved in generating the image and determining the IMT. In [16], an expert (physician) marks several points manually on the Intima, Media and Adventitia in an ultrasound image. Curves are fit for these marked points. The distance between two diametric points in parallel curves denote the dynamic Intima-Media thickness and lumen diameter. In [17], polynomials were fit to a sequence of images to determine the shape of the carotid artery, and the distension wave form was estimated from these curve fits. In [18], a sequence of B-mode images are considered and regions of interest are manually marked. Using multiresoultion analysis the contours of CCA are obtained from the marked regions.

In [13], Radio Frequency (RF) ultrasound signals were used to assess the IMT, Lumen diameter and distension waveforms. However, RF ultrasound signals were acquired from an echo scanner (image based system) using a dedicated data acquisition system. The imaging system is used to position the ultrasound sensors to obtain RF signals that have significant reflections from the walls of the CCA. This is an important step as mis-positioning would lead to high noise signals with very-little contributions from the walls of CCA. The RF signals acquired were low-pass filtered to remove noise. An adaptive thresholding scheme was used to determine the intima, media and the lumen diameter. In [14], as in [13], RF ultrasound signals were acquired from an image based system using a dedicated data acquisition system. And positioning of the sensor were based on the imaging system. The acquired signal was filtered with an adaptive band-pass filter. Using an adaptive thresholding scheme the diameter of the lumen was estimated. The adaptive thresholding scheme presented in both [14,13] were both similar with a contour tracking around the peaks and an exponential decay between two peaks. The rate of exponential decay being changed adaptively depending on the size of the last peak encountered. Both filtering and wall detection in [14,13] involves making a certain educated guess on deciding the parameters involved. In summary, the three primary tasks, when using systems that acquire RF signals, are (1) Positioning of the sensor to record signals with significant contributions from the walls of CCA. (2) Filter the acquired signals to remove clutter. (3) Detect the walls of CCA and determine the lumen diameter from the filtered signal. Furthermore, all the three steps have to be done in real time.

Unlike [13,14], ARTSENS is independent of any imaging system. Positioning of the ultrasound, Fig. 2, sensor to obtain signals with significant contributions from the CCA is explained in detail in Section 2. Here, a sparse signal processing approach is taken to filter the signal. A train of Gaussian Modulated Sinusoidal (GMS) pulses are fired at the CCA, Fig. 3. The reflections (echoes) due to each GMS pulse in the pulse train is acquired and recorded. These echoes are