Application of machine learning for IMT segmentation in CVD diagnosis: A review

Tareeq Zaid*, Dr. Nagshettappa Biradarb,

aElectronics & Communication Engineering, BKIT, Bhalki, India
bElectronics & Communication Engineering, BKIT, Bhalki, India

Abstract: Cardiovascular disease (CVD) is one of the leading cause of death. Assessing of CVD is performed from carotid artery measuring the Intima Media thickness (IMT) through ultrasound imaging. However, various artefacts pertaining to biological, instrumental and noise sources reduces the quality of segmentation of the arterial walls. This review addresses the issues pertaining to noise characteristics observed in ultrasound imaging along with methods of semi and fully automated methods of segmentation. The inference drawn from this review leads to potential applications of machine learning methods in automated methods of segmentation of arterial walls in ultrasound imaging, thereby improving the diagnosis of the CVD.

Keywords: Ultrasound imaging, Speckle noise, carotid artery, Intima Media thickness (IMT), machine learning

1. INTRODUCTION

Cardiovascular diseases (CVD) are found to be leading cases of death in a recent survey conducted by the world health organization [1]. It also remains to be the single biggest cause of mortality [2]. Projections from the world health organization suggest that CVD deaths will reach 25 million per year by 2020. This creates a necessity to develop robust and effective treatments in CVD treatments. Atherosclerosis is observed to be the pathological cause in majority of cardiovascular events, and progression of atherosclerosis tends to increase risk of future cardiovascular events. Vascular ultrasound techniques are now commonly used as surrogate markers in clinical trials of novel CVD therapies.

Several interventional studies indicated coronary angiography as method of assessing the risk of CVD in individuals [3][4][5][6]. However, the current understanding of atherogenesis has signified limitation in this technique. Other limitations concerning the angiography involve low resolution, exposure to x-ray radiation and the invasiveness of the procedure. Although angiography is still considered as a gold standard in evaluating CVD, due to its limitations, other methods such as magnetic resonance imaging, cardiac computed tomography and ultrasonography are some of the methods that have generated a significant research interest.

Ultrasound on the other hand is a simple, inexpensive and non-invasive technique, which also enables one to visualize the arterial wall itself due to its penetrating nature. Also, the technique does not expose the patient to x-ray radiation and is associated with higher inter and intra observer reproducibility in well controlled research settings [7]. The ultrasound imaging also permits multiple serial measurements to accurately monitor changes in atherosclerosis. Studies have shown that changes in Carotid Intima Media Thickness (CIMT) measured from B-mode ultrasound images acts as a surrogate marker for CVD, indicating coronary atherosclerosis and in predicting clinical coronary events. While one of the issues in ultrasound imaging involves visualizing the carotid arteries (distorted due to speckle noise), another major issue is in estimating the boundary locations and narrowing onto their exact location. However, until recently, the method for segmenting the arteries in ultrasound imaging was mainly done through a semi-automated approach with visual inspection from the sonographer. This review addresses the issue of localizing source through quantitative imaging involving machine learning techniques. Also this review includes the issues pertaining to image quality assessment considering such quantitative approaches.
The paper is constructed as follows, the first section of introduction describes about the cause and concern in assessing CVD, along with suitable imaging methods in assessing Intima media Thickness (IMT) which could prove as a potential biomarker in identifying CVD. The first section also explains about the physical characteristics of ultrasound imaging and its role in identifying IMT along with its imaging characteristics and limitation. The second and third section deals with the existing literature in addressing the issue of image quality assessment in ultrasound imaging and source localization. Finally, the last section identifies the research gap and arrives at the conclusion.

**Background**

The ultrasound imaging has been widely used in identifying the Intima Media Thickness and in medical diagnostic methods, mainly due to its non-invasive nature and its cost effectiveness. However, unlike other imaging techniques, many of the objects and artefacts from the ultrasound are due to physical properties of ultrasound beams such as reflection, refraction and attenuation. Some of the physical characteristics that are involved in ultrasound imaging are as follows:

1. Frequency: The frequency in ultrasound imaging is defined as the number of cycles or pressure changes that occur in 1 second. The units of frequency is defined as cycles/second or hertz. The typical range of ultrasound ranges from 2 Mhz to 10 Mhz range.

2. Propagation Speed: Propagation speed is the speed at which the sound travels through the medium, the medium characteristics such as density and stiffness is what determines the speed in ultrasound imaging.

3. Ultrasound Interaction with Tissue: The property of acoustic impedance which is a measure of product of density and propagation speed is measured when the beam is reflected from the boundary of two different materials. This property directly correlates to the strength of the echo, which is significant during measuring of soft tissues. The percentage of reflection of ultrasound at boundaries is mentioned in table 1 [8].

**Table 1: Percentage reflection of ultrasound at boundaries.**

<table>
<thead>
<tr>
<th>Boundary</th>
<th>% Reflected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat/Muscle</td>
<td>1.08</td>
</tr>
<tr>
<td>Fat/Kidney</td>
<td>0.6</td>
</tr>
<tr>
<td>Soft tissue/water</td>
<td>0.2</td>
</tr>
<tr>
<td>Bone/fat</td>
<td>49</td>
</tr>
<tr>
<td>Soft tissue/air</td>
<td>99</td>
</tr>
</tbody>
</table>

However, rough edges have features that produce echoes in many directions that help in providing imaging of irregularly shaped objects. This is especially useful when ultrasound beams hits the object at non-normal angle of incidence.

In present day ultrasound imaging, a rapid sequence of B-scan images is displayed such that movement is visualized as it occurs. The modern equipment typically shows 15-60 image frames per second.

It is observed that the images show a smoother appearance when the number of frames/second increases. However, as seen in other imaging techniques, ultrasound imaging also experiences artefacts, which occur due to some of its physical characteristics.

**Artefacts associated with Ultrasound imaging**

To understand the artefacts associated with the ultrasound imaging, certain basic assumptions are made which are as follows:
1. Sound waves travel in straight lines
2. Reflections occur from structures along central axis of the beam.
3. Intensity of the reflection corresponds to the reflector scattering strength
4. Sound travels at exactly 1540 m/s
5. Sound travels directly to the reflector and back

However, the major artefacts that are encountered in ultrasound imaging are mentioned as shown in table 2.

**Table 2: Major artefacts that are associated with ultrasound imaging**

<table>
<thead>
<tr>
<th>Artefact</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverberation</td>
<td>multiple equally spaced lines along a ray line, caused due to ultrasound beam moving back and forth between tissue boundary</td>
</tr>
<tr>
<td>Ring Down</td>
<td>small crystals that resonate at ultrasound frequency, caused due to beam emitted after initial reflection received by transducer</td>
</tr>
<tr>
<td>Mirror Images</td>
<td>real object being reflected in the ultrasound image, caused due to sound bouncing off the diaphragm</td>
</tr>
<tr>
<td>Reflections</td>
<td>similar to mirror images but caused by multiple reflections</td>
</tr>
<tr>
<td>Enhancement</td>
<td>occurs as abnormally high brightness, caused when sound travels with an attenuation rate lower than the surrounding tissue</td>
</tr>
<tr>
<td>Attenuation</td>
<td>appearance as dark images due to lower intensity of the transmitted beam</td>
</tr>
</tbody>
</table>

However, these artefacts are significant in intravascular ultrasonic imaging, recent studies has indicated a correlation with the thickness of the carotid artery IMT in patients with slow coronary flow [9].

**Significance of vessel wall segmentation**

The wall of the artery consists of 3 layers involving the innermost, middle and outermost layers known as intima, media and adventitia respectively. In the common carotid artery (CCA), the segmentation of the artery walls involves the tracing of interface such as lumen-intima (LI) and media-adventitia (MA) interface.
However, the effects of these artefacts play a major role in assessing the IMT layers in ultrasound imaging. For example, when intima layer is fused with media layers, it results in poor acoustic impedance of the adjacent layers, due to the highly echogenic nature of adventitia layer it appears as bright grey.

The computer based diagnosis methods primarily aim at tracing LI and MA boundaries (fig. 1). Studies have shown that it is possible to identify the IMT by simply measuring the distance between LI and MA boundary (fig. 1). By segmenting the CCA walls from B-mode images, the distance between the near and far media layers can be calculated along with cardiac diameter values in different phases in cardiac cycle.

2. ISSUES INVOLVING VESSEL WALL SEGMENTATION

Segmenting the vessel involves many issues pertaining to clinical, biological variability and technical bottlenecks. Some of the significant issues are mentioned in this section.

A. Biological variability in vessel wall segmentation

A change is observed in the morphology of the carotid artery during the presence of pathology or plaque. According to Mannheim consensus, plaque is identified to be a focal structure encroaching into arterial lumen in 50% of surrounding IMT value measured from media-adventitia interface to intima-lumen interface [10]. Considering from the geometrical perspective, plaque causes a hill-shaped carotid wall, which is not represented as horizontal and straight. This leads to the main issue in segmentation methods, most of these methods perform optimal only when vessels are viewed as horizontal, regular and straight.

B. Variability pertaining to instrumentation

The variability in ultrasound instruments occurs when operators vary the parameters for different patients causing differences in ultrasound images. However, most of the segmentation does not address the issue of instrumentation variability. The techniques developed for segmentation are scanner dependent, leading to alterations in image characteristics, which require retraining, tuning and optimizing of parameters.

C. Noise sources

Speckle noise is found be one of the major sources of noise during ultrasound imaging. This is especially prevalent in carotid longitudinal images. However, few of despeckling strategies include local statistics, median filtering, pixel homogeneity, geometric filtering etc. Other sources of artefacts pertaining to imaging of carotid artery through ultrasound involve blood backscattering and shadow cones.

3. DISCUSSION OF EXISTING TECHNIQUES

On the basis of addressing the biological variability, a study on the variations in anatomy of the carotid was performed by Lucev et. al [11]. Rossi et. al [12] proposed an automated algorithm for detecting the CA in the image frame, without user interaction. Further, to localize the adventitia layers tracing of the CA a user-independent technique was proposed by Molinari et. al [13], which tested on CA morphology of healthy vessels vs. vessels with plaques. Though, this method shows significant improvement on the basis of practicality in usage, this inter induces instrumental variability causing imaging artefacts.

The imaging parameters of the ultrasound are scanner dependent leading to different artefacts caused by the instrumentation. Methods such as normalization of images, linear grey scale mapping were proposed to make the imaging more scanner independent. An study was conducted using different ultrasound imaging scanners in automating the method of separating lumen points from tissue by Molinari et. al [13] based localized statistics.

As mentioned previously, the most prominent artefact in ultrasound imaging in identifying the carotid artery is the speckle noise which is caused by locally correlative multiplicative noise. Studies have indicated speckle noise to be one of the major limiting factor in visual perception of the expert while assessing ultrasound imaging [14]. Loizou et. al [15] introduced a speckle reduction filter based on mean and variance of pixel neighborhood also known as Linear Scaling Mean Variance (LSMV). However, due to different gain settings and comparability of tissues, methods of normalization and standardization were introduced using blood echogenicity as a reference point.

A method of carotid wall segmentation was first proposed by Touboul et. al [16] which was based on edge detection, followed by Pignoli and Longo [17] with the aim of aiding IMT measures based on appearance of CCA. An edge based segmentation method based on image gradient was proposed by Ligouri et. al [18] by considering horizontal placement of artery in B-mode images. However, the intensity that was measured was different due to noise. Therefore, to address this issue a statistical based thresholding was
implemented while computing the image gradient. Although, the technique reduced the noise characteristics to a negligible level, it lacked the essence of automation in terms of segmentation process. Stein et. al [19] proposed a fully automated technique to measure the IMT of the carotid wall based on gradient method. They inferred that automated methods of segmentation yielded faster, reproducible, accurate and user independent, however, this method provide an estimation of CCA wall segmentation rather than the real CCA wall segmentation. Faia et. al [20] proposed another gradient based segmentation method, however, as previously indicated, although Ligouri et. al [21], it suffers the problem of superimposed noise precluding a proper individualization of LI and MA transitions. Overall, the gradient based image segmentation seemed advantageous, it suffered from various artefact including the focusing artefact, leading to change in vertical direction of the focus position. Also, a significant change in the intensity of the image and grayscale representation was observed.

Variability of instruments in ultrasound imaging was addressed by novel methods of dynamic programming [22]. The methods of dynamic programming were to mainly address the issues pertaining to variability occurred due to operability of the equipment, Wendelhag et. al [23] proposed the concept of dynamic programming to automate detection of echo interfaces. Boundary features such as echo intensity, intensity gradient and boundary continuity were linearly combined (cost function). Further development in dynamic programming involved Multiscale analysis proposed by Liang et. al [24]. This method reduced the computational burden through an iterative fashion of identifying the global position of the artery from coarse to fine.

Of all the segmentation methods pertaining to carotid artery, snake based methods are considered to be the most prominent and significant method. The significance of this method as compared other method is its ability in differentiating the LI and MA boundaries. The method also incorporates the dynamic programming to minimize the global energy function. However, issues concerning the snake method involve optimization of parameters, initialization of snake points and sensitivity to noise.

In 2002, Gutierrez et.al [25] proposed automated technique for estimating carotid IMT and lumen diameter based active contours. These contours are subjected to three different phases namely internal, external and damping which corresponds to contour curvature, local magnitude and velocity of each contour respectively. The proposed method was able to smooth and stabilize the contour evolution by using damping force. However, few limitations of this method include sensitivity of noise factor and monitoring of IMT changes with respect to time. Loizou et. al [26] addressed the issue of pre-processing and standardization of ultrasound imaging to overcome limitations concerning the snake method.

Of these limitations, one of the significant limitations involving the speckle noise was presented by C.P Loizou et. al [27] which is caused due to blood rouleaux. A preliminary normalization and despeckling was performed to address the issue noise sensitivity.

A combined approach of localized statistics with snake based approach was proposed by Delsanto et. al.[28, 29] for performing IMT measurement. The proposed method involved locating carotid artery and measuring the IMT, to automate the process of CCA segmentation, a bidirectional histogram based clustering was performed with mean and standard deviation. Subsequently, Molinari et. al [30, 31] proposed a segmentation technique to segment near wall and diseased vessels. The ROIs were further identified using near and far adventitia profiles resulting in 3 clusters namely lumen, intima and media along with adventitia layers through the fuzzy K-means classification. This technique not only reduced the IMT measurement error but also performed robust segmentation of plaques with a misclassification rate of 12±4%.

Fig 2: B-mode ultrasound image from carotid artery

Destrempes et. al [32] proposed a segmentation strategy considering small vertical ROIs containing IMT complex with analyzed Radiofrequency signal using the Nakagami mixture model and stochastic optimization. This method assumed lumen corresponding locally to the distribution to lower mean, IMT corresponding to mixture and adventitia corresponding to higher mean distribution.

A lesser known but important class of segmentation methods involving CCA wall is based on Hough transformation. Hough transforms are used to detect circles and lines enabling segmentation of longitudinal and traverse B-mode images which is reflected as straight and circular respectively. The LI and MA boundaries were traced independently from the longitudinal images and the distance between them was measured as IMT. The method is particularly effective during processing the vessels which were affected by plaques having smaller walls.

The machine learning techniques addresses the issues pertaining to manual risk assessment, particularly with near and far wall segmentation (fig. 2) [33].

Rosa-Maria et. al [34] proposed a novel technique in automatic detection of carotid IMT segmentation using neural networks based machine learning framework. It involves a combination of Multi-Layer Perceptron and binary classification to identify the IMT contours. Similar works involving IMT segmentation using neural networks and hybrid neural network-genetic methods are proposed in [35] [36] [37] respectively. Nagaraj et. al [38] proposed an edge based segmentation methods from the longitudinal ultrasound images using structured random forest for IMT quantification resulting in a minimum standard deviation of 0.66mm±0.14.

Other methods of segmentation using machine learning involves identifying and extracting grayscale features
to determine the variability in wall thickness. Araki et al. [39] proposed a PCA based polling strategy in machine learning framework in assessing the coronary artery disease in ultrasound imaging. Classifiers such as SVM and CPAR using the heart rate variability as a potential feature resulted in 85-90% of overall accuracy as proposed by Lee. et al. [40].

CONCLUSION

From the proposed study reviewing methods of segmentation in ultrasound imaging for assessing the carotid wall artery for CVD, various factors such as noise characteristics, imaging parameters, etc. contribute to the process of segmentation. However, speckle noise obtained from ultrasound imaging has major influence in the methods of segmentation of the carotid wall pertaining to IMT. Along with the conventional methods of semi-automated and automated based segmentation, the application of machine learning techniques such as MLP and PCA has improved the quality of segmentation particularly the near wall and wall segmentation along with interfaces of LI and MA boundaries. Therefore, by further developing the applications pertaining to machine learning methods in segmentation, a more robust and efficient wall segmentation can be obtained which would facilitate in the assessment in CVD using ultrasound imaging.

REFERENCES

[7]. Bots ML, Grobbée DE. Intima media thickness as a surrogate marker for generalised atherosclerosis, Cardiovasc Drugs Ther., 2002, vol. 16 (pg. 341–351)


