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Boundary detection in carotid ultrasound images using dynamic programming and a directional Haar-like filter

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ABSTRACT

The intima–media thickness (IMT) of the carotid artery, obtained from B-mode ultrasound images, has recently been proposed as one of the most useful indices of atherosclerosis and can also be used to predict major cardiovascular events. Ultrasonic measurements of the IMT are conventionally obtained by time-consuming manual tracing of the interfaces between tissue layers. We propose a computerized method to detect the boundary of the intima–media complex using a directional Haar-like filter that can account for the slope of the boundary in an image. The directional Haar-like filter extracts a directional boundary feature as an image feature in the region of interest, which is used to compute a cost function. A cost function includes not only the directional Haar-like filtering value but also the geometric continuity that is computed for every pixel in the region of interest. The optimal boundary pixels are detected by using a dynamic programming approach that searches for the pixel that minimizes the cost function in each column of the image. We compared the performance of the proposed method with that of manual methods performed by two radiologists. The results showed that our approach produces very similar results to those based on manual tracing, and there was no statistically significant difference between the IMT measurements segmented manually and those analyzed using our method.

1. Introduction

Carotid intima–media thickness (IMT) has proven to be an early marker of atherosclerosis and a strong predictor of future cardiovascular events such as stroke and myocardial infarction [1]. An increased IMT is also associated with the prevalence of cardiovascular disease and is involved in atherosclerosis in other arterial systems [2–4]. The IMT of the carotid artery is usually measured using a high resolution B-mode ultrasound image, because it is noninvasive, safe, inexpensive, and relatively simple. Most researchers have traced the intima–media complex (IMC) manually to determine the IMT. However, the conventional manual tracing method has the drawback of inconsistency since the performance is dependent on the subjective judgment of an observer. Moreover, this procedure is very time consuming. Therefore, this method is inappropriate for projects requiring high consistency, such as analyzing a large database of carotid artery sonographic images.

To avoid these problems, various computerized methods have been proposed for detecting the IMC in carotid artery images. Selzer et al. [5] described a multi-step procedure. In their method, the approximate position of the boundary is identified first by manually placing a small number of points on the vessel interface. Guided by this approximation, a set of conditional edges is generated by applying a maximal local intensity gradient criterion. The strengths of these edges are then evaluated and weak edges are eliminated. Obviously, the subjectivity by an observer is not completely eliminated since an initial input is required.

Dynamic programming has been used to detect the boundaries of the intima–media [6–8] from multiple-image features such as intensity and gradient. These methods produce reproducible measurements of the ultrasonic data, but some subsequent manual correction is required. In addition, the process involves three weighting factors that have to be tuned using a training procedure [8], which is based on tracings by experts.

Cheng et al. [9] suggested using the snake approach [10] to detect the boundaries of the intima–media complex. This approach is very sensitive to the initial approximation of the contour, which must be placed close to the actual boundary of interest or the snake will not be attracted. In addition, the

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weighting factors representing elasticity and rigidity have to be tuned. Cheng and Jiang [11] subsequently proposed another automated procedure that uses dual dynamic programming. This method is based on a cost function that includes geometric constraints constructed using anatomical knowledge. This approach is less affected by speckle noise than previous dynamic programming techniques [8]. However, additional weighting factors are required to smooth the dual curve, and these must be tuned to match the characteristics of the particular ultrasound instrumentation. More recently, Loizou et al. [12] revisited the snake approach. They preprocessed ultrasound data by normalization and speckle reduction, and then used an improved procedure for initializing the snake. However, the ability of this technique to deal with irregular boundaries was not investigated.

In this paper, we present a semi-automatic boundary detection procedure based on dynamic programming and use of a directional Haar-like filter. We use dynamic programming [13] to achieve a global minimum search of image features extracted using a directional Haar-like filter. Our method uses a Haar-like filter to take into account the slope of the boundary, whereas most previous works have not dealt with the sloping boundaries that occur in carotid artery images. By applying a directional Haar-like filter, we were able to increase the robustness of edge detection against speckle noise, weak edges and echo gaps in the ultrasound images.

The rest of this paper is organized as follows: in Section 2, we describe our image acquisition techniques and the characteristics of carotid artery ultrasound images. We also describe the segmentation procedure that we use to detect the boundary of the intima and adventitia layers. The results from this method are evaluated in Section 3. Finally, we draw some conclusions in Section 4.

2. Materials and methods

The B-mode longitudinal ultrasound images of the common carotid artery used in this study were acquired using an Accuvix XQ (Medison Co. Ltd., South Korea) ultrasound scanner with a linear 5–12 MHz transducer. The artery was examined by turning the neck of the subject to the left and right, with the transducer positioned at the side of the neck. This approach maximizes the lumen in the longitudinal plane so as to produce a good image of the near and far wall of the artery. The intima–media complex of the artery is identified by characteristic double lines. The images were then saved in DICOM format using the SonoView software.

2.1. Image characteristics

A representative image of the carotid artery is shown in Fig. 1(a). The near and far walls of this artery are made up of the adventitia, media and intima, which are distinct tissue layers. Fig. 1(b) shows a close-up of the region of interest in Fig. 1(a), consisting of the echo zones Z1–Z4 and the vessel interfaces I1 and I2, which correspond to the intima–media complex at the far wall of the carotid artery. The leading edges I1 and I2 of echo zones Z2 (intima) and Z4 (adventitia) are, respectively, the lumen–intima and media–adventitia interfaces of the far wall.

The IMT is defined as the distance between I1 and I2. As shown in Fig. 1(a), the echo zones of the near wall are weaker than those of the far wall, due to the overlap of echo pulses. Therefore, the lumen–intima and media–adventitia interfaces of the far wall is the preferred site for the IMT measurements. Manual measurements of the IMT are made by placing calipers on the leading edges I1 and I2, which are traced manually. A close-up image of the intima–-media complex at the far wall of the artery and the calipers are shown in Fig. 2(a). Fig. 2(b) illustrates the placement of calipers on the anatomical structures of the far wall of the artery.

2.2. An image feature based on a directional Haar-like filter

2.2.1. Problem statement

Detecting the boundaries of the intima and adventitia layers of the carotid artery from ultrasound images is challenging because of speckle noise, imaging artifacts and weak edges due to random scattering. In addition, some parts of an image may be missing because of echo dropout or acoustic holes, which increase the difficulty of detecting the correct boundaries. Additionally, the IMC is not completely horizontal in the image, due to variables such as the position and the angle of the probe with respect to the arterial wall during the acquisition of the images. To overcome the difficulty, we combine a global optimization approach using dynamic programming with the use of a directional Haar-like filter.

2.2.2. Cost function

Cost functions are built for I1 and I2. If a user specifies an $M\times N$ region of interest, all possible boundaries B_N can be considered as polylines with N nodes:

$$B_N=\{\boldsymbol{p}_1,\boldsymbol{p}_2,\ldots,\boldsymbol{p}_{N-1},\boldsymbol{p}_N\}, \tag{1}$$

where the pixels $\boldsymbol{p}_{N-1}$ and $\boldsymbol{p}_N$ are horizontal neighbors, and N is the horizontal length of a contour line. The cost function $C(B_N)$ is defined as the following sum of local costs along a candidate boundary B_N:

$$C(B_N)=c_f(\boldsymbol{p}_1)+\sum_{i=2}^{N}(w_1c_f(\boldsymbol{p}_i)+w_2c_g(\boldsymbol{p}_{i-1},\boldsymbol{p}_i)). \tag{2}$$

At a point $\boldsymbol{p}_i$, the local cost is made up of two terms, an image feature term $c_f(\boldsymbol{p}_i)$ and a geometrical force term $c_g(\boldsymbol{p}_{i-1},\ \boldsymbol{p}_i)$.

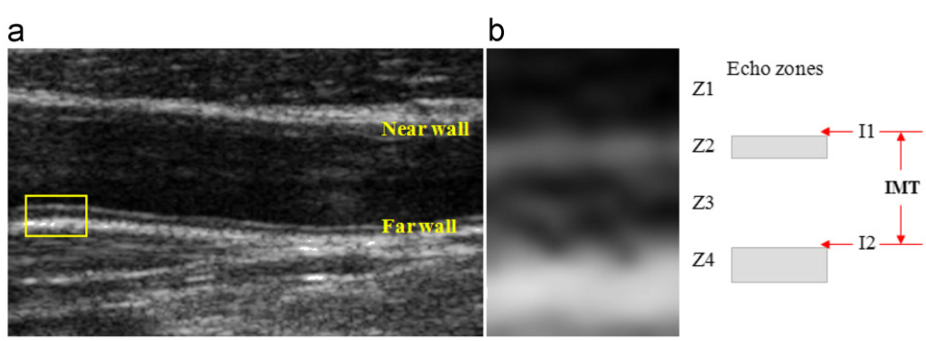

Fig. 1. The intima–media complex of the carotid artery: (a) B-mode ultrasound image of the arteryand (b) echo zones and interfaces corresponding to the intima–media complex of the far wall of the artery.