Automatic Detection of the Intimal and the Adventitial Layers of the Common Carotid Artery Wall in Ultrasound B-Mode Images Using Snakes

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Abstract
This study presents a novel automatic system for detecting the intimal and adventitial layers of the far common carotid artery (CCA) by applying the snake techniques. Cohen’s snake is also modified and some criteria are added for our applications. In addition, the oscillation problem of using snakes is solved by properly choosing the time step from analysis of the frequency response of the filters. The snake scheme combined with a time diminishing window and an external force makes it possible to detect the intima-media complex of the far CCA. Besides, a cost function assists the snake in selecting the optimal shape of the adventitia layer. This mechanism is also helpful when there are plaques on the CCA wall. Moreover, this study compares the proposed snake and ziplock snake with respect to the manual extraction contour. According to that comparison, the system can automatically detect the intimal and adventitial layers. In addition to that it does not need any manual correction and it is noise-resistant, the proposed system allows a user to quantitatively measure an important predictor of heart infarction and strokes.

1. Introduction
The intima-media thickness (IMT) of the common carotid artery (CCA) can be used to predict major cardiovascular events like myocardial infarction and stroke [1-2]. Previous studies have indicated that increases in the IMT of the CCA are directly associated with an increased risk of myocardial infarction and stroke in elderly adults without a history of cardiovascular disease. Also, the IMT can be viewed as a descriptive general index of individual atherosclerosis [3]. High resolution ultrasonographic imaging provides a noninvasive means of estimating the IMT of the human carotid arteries. To measure the IMT, most research groups used the manual tracing method to delineate the boundaries of an intima-media complex [3-5]. The manual tracing method is not only time-consuming, but also less reproducible. In addition, the tracing results vary according to the training, experiences, and subjective judgment of the physicians. This method is also inappropriate for analyzing a large database with ultrasound carotid artery images. Thus, Wendelhag et al. developed an automated computerized analyzing system to extract the boundaries of the intima-media complex by dynamic programming [6]. However, the system requires some manual corrections after automatic tracing, indicating that it is not robust.

To improve the convenience, this study presents a novel automatic system for extracting an intima-media complex based on the active contour model [7-9]. In general, segmentation of a digitized image involves extracting the regions or the boundaries of interest. Conventional methods can be categorized as either region based or edge based, depending on the technique used. For the intention of the intima-media complex extraction, the edge based method is a better solution than the region based one since it can directly identify the layer boundaries instead of analyzing the whole region. Moreover, the region based segmentation is somewhat more time-consuming than the edge based scheme [9]. Furthermore, the region-based method encounters a problem of labeling and linking after region extraction. If some discontinuities arise, some prior knowledge is necessary for determining which object belongs to the same class. In contrast, the active contour model of Kass et al. [7] can position itself into a local minima of an objective function where provides a stable state. The user can derive a special snake or modify the external forces to attract the snakes into the interesting boundaries by an iterative process. Many modifications are derived from the original active contour model for special purposes. L. D. Cohen et al. [8] proposed a balloon’s model for the snake and, in doing so, used the finite element method to calculate the function of continuity. This deformable model is expanded to 3D for processing the 3D MR images [9]. Neuwenschwander et al. [10], proposed an ‘ziplock’ snake which acts as a growing snake, expanding from both end points given by the user and ultimately meeting each other. The ziplock snake does not need any initial contour except that the given points must be closed to a well-defined contour. However, it is limited in that it can not avoid the noise effect if the noise is near the contour. Lai and Chin [11] proposed another
deformable contour model for extracting rigid body in a noisy environment. Although capable of detecting rigid body motion, their model is inappropriate for detecting soft tissue such as the intima-media layer. In this study, we modify the Cohen’s snake and propose some criteria for this application. Owing to that the snake needs a mechanism to place it in close proximity to the area of interest, an identification procedure is proposed to provide the initial curve for the snake. The proposed procedure can also reduce the computational time and avoid the noise effect in the artery lumen.

2. Materials and Methodology
The CCA was examined by initially turning the neck of the study subject slightly to the left side. The transducer was positioned at the lateral side of the neck without any compression of the inner jugular vein. The lumen was then maximized in the longitudinal plane with an optimal image of the near and the far vessel wall of the CCA. Thus, typical double lines were observed as the intima-media complex of the artery. The images were digitally stored on a recorder.

A. Identification of initial snake contour
After the recording, the stored images were transferred into a PC for off-line analysis. Owing to that the snake needs a mechanism to place it in close proximity to the area of interest, the initial contours are given by manual input [7,8]; otherwise, some algorithms are proposed for different applications [12]. Herein, a robust identification procedure is proposed and applied on the ultrasound images to obtain the initial contour \( C \) for snakes. The user only needs to choose the starting and ending points, \( P_s \) and \( P_e \), which include the interesting measurement region of the IMT. The given points should be located above the intima in the artery lumen. A sampling line in discrete form \( l(p) = \{ P_j = (x_j, y_j) \} \) from \( P_s \) is then radiated downward to search the intimal layer of the far CCA. Once obtained, the intimal boundary searches along the right side to detect the whole area of interest. However, to avoid the noise effect, the gradient values, thickness, and continuities are considered for judgment. Notably, the gradient value is used instead of the gray-level value because, based on our many experimental observations, the former is better than the latter in terms of resisting the noise effect. Let \( g(x, y) \) be the gradient value at pixel \((x,y)\), as defined in Eq. (9).

The detailed identification procedure is omitted due to the page restriction.

After the initial contour identification procedure, a curve near the intimal layer can be detected as illustrated in Fig. 1. The initial contour identification procedure not only provides a noise-resistant initial contour, but also significantly reduces the computational time. Results obtained from the intimal boundary are used as the initial curve to identify the adventitia by moving it downward about 0.05 cm. This downward movement is based on the consideration of the anatomical reason in which the thickness of intimal layer should not be more than 0.05 cm.

B. The Proposed Snake Model
Since the pioneering work of Kass et al. in developing the snake technique, numerous researchers have applied and modified it for edge detection, pattern recognition, motion tracking, and salient extraction via an energy-minimization process [14]. In a geometrical configuration, a two-dimensional snake is a parametric contour represented by \( v(s) = (x(s), y(s))^T \), where \((x, y) \in \mathbb{R}^2\) denotes the spatial coordinates of an image and \(s \in [0,1]\) represents the parametric domain. The snake adapts itself to an image by a dynamic process that minimizes an energy function as follows,

\[
E_{\text{ext}}(v) = \int w_1(s) |v'(s)| + w_2(s) |v''(s)| \, ds ,
\]

where \(E_{\text{int}}(v)\) denotes the internal energy derived from the physical characteristics of a snake, and \(E_{\text{ext}}(v)\) is the external energy due to some relevant features such as the gradient of edges, lines, regions [15], and texture [16]. The energy function of (1) implies that the final stable state of searching for an edge depends not only on the gray-level gradient at a specific point, but also on the spatial correlation and/or some knowledge-based criteria. The governing equation incorporates the assessment of edges by combining the initial estimation, desired edge properties, continuity and the curvature of a contour, and some other constraints, into a single, dynamic process. For a general application, the internal energy can be represented by

\[
E_{\text{int}}(v) = \int \left[w_3(s) |v'(s)| + w_4(s) |v''(s)| \right] ds ,
\]

where \(w_3(s)\) and \(w_4(s)\) denote the elasticity and rigidity of the snake, respectively. The mechanical properties of snakes can be controlled by tuning these two factors. However, selecting these two factors is based on the demand for the applications and the characteristics of objects to be traced. Notably, increasing both weightings may enhance the effect of the physical properties of the model, thereby diminishing the influence of the external forces. To design a robust automatic system for extracting the intimal and the adventitial layers, the two factors are assumed to be independent of position and thus are fixed to constants.

With respect to external forces, they are generally divided into image forces such as gradient, and additional forces given by the user or based on the application. Based on the observations that the intimal and adventitial layers have a conspicuous difference from its neighboring tissues, the Macload operator [17] is implemented and the gradient image is applied as the image force. However, our results reveal an interface between the intimal and the adventitial layer, referred to herein as the sub-intimal region and illustrated in Fig. 2. The sub-intimal region might make it difficult for the snake to identify the
adventitia because the sub-intima lies in close proximity to the adventitia. The distance is only two to four pixels (pixel size=0.0096 cm) in normal patients. Therefore, a criterion must be developed to enhance the adventitia and reduce the effect of the sub-intimal region. Thus, in this study, a vector \([-1 0 1\)^T\] is used to enhance the edge having a black region above it and white region under it from the observer’s view. Thus the external forces can be defined as

\[
E_{ext}(v) = -\int_0^1 g_m \left( f_M * I \right) + D * I \right) dv = -\int_0^1 F(v) dv ,
\]

where \( D = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \)

where \( f_M \) represents the Maclock operator, \( I \) denotes the raw image, \( g_m \) is the gravity constant, \( A \) is a positive value for weighting, and \( * \) is a convolution operator. In addition, \( \Omega \) defines a local area in which the gravity is assumed to be effective to current position \( v \). In this study, we choose \( A \) as 1.5 for all experiments. Notably, the external force may produce a negative force which represents a repulsion force to snakes. This repulsion force is normally located on the sub-intimal region to repulse the snakes from the sub-intimal region to the adventitia. This design is appropriate for both intima and adventitia layer tracking. When identifying the intima, the snake is not be affected by the adventitia because the sub-intimal region provides a negative force to repulse and prevent it from attracting from the adventitia. This design is also based on the assumption that the initial contour for identifying the intima always lies above the sub-intimal region. The proposed initial contour identification procedure ensures this. To reduce the computational time, the region for computing the gray-level gradient is restricted to an area in close proximity to the initial curve. The initial shape of the snake while identifying the intima is based on the results of the initialization described in section 2A. A final result would be obtained after a dynamic minimization process of (1) with respect to \( v \), which satisfies the Euler-Lagrange equation:

\[
\frac{\partial}{\partial t} \left( \frac{\partial}{\partial x} \left( w_i \frac{\partial v_i}{\partial x} \right) + \frac{\partial}{\partial y} \left( w_i \frac{\partial v_i}{\partial y} \right) - F(v) \right) = 0 ,
\]

plus boundary conditions.

While \( \frac{\partial v}{\partial t} \) tends to zero after some iterations, a stable state would be obtained and the snake stops. For a discrete form of Eq. (4), the formula can be written as

\[
\frac{v_i - v_i^{n-1}}{\tau} + A^{o}V - F = 0 ,
\]

where \( A \) is a pentavector and \( V \) denotes the vectors of positions \( v_i \). The parameter ‘h’ used in \( A \) denotes the spatial sampling distance which is defined as 1 in our study. More over, \( w_i = 0.6 \) and \( w_i = 0.4 \) are fixed without change. To calculate the next \( v_i \), the previous iterative positions are used as

\[
v_i' = v_i^{n-1} + \tau [F(v_i^{n-1}) - A^{o}V - F] ,
\]

where \( \tau \) represents the sampling time interval. To prevent the oscillating problem, an appropriate choice of sampling time interval is important. This problem can be avoided by manual tuning \([7]\) and the external force is modified to limit the updating step \([8]\). Closely examining Eq. (6) reveals that \( A \) is not only a high-pass filter, but also an amplifier. The next iterations of the snake are calculated by subtracting the high frequency component from current items and, then, combining the external force with a factor \( \tau \). This differs from that of Cohen’s snake, in which the next position is calculated by smoothing the current items of the snake with a low-pass filter and combining it with the external force. The choice of \( \tau \) affects the convergence of the snake. Choosing a smaller value implies a longer time to converge to a static state. In contrast, choosing a larger value implies that the snake oscillates and even diverges. For an appropriate choice of the time constant \( \tau \), we suggest that \( \tau A \) should be a unit high-pass filter without amplification. Restated, \( \tau \) is the reciprocal of the maximum absolute value of the frequency response of \( A \).

\[
\tau = \frac{1}{\max|\hat{H}(A)|}
\]

where \( H(A) \) denotes the frequency response of vector \( A \). Based on this definition, the snakes does not diverge and the choice of time constant becomes easy to handle.

Fig. 3 depicts the frequency response of the three normalized filters: the curve with ‘+', ‘*', and ‘o' symbols denote the filters used in Cohen’s snake, the derived high-pass filter, respectively. The external force is another factor which may cause the snake to become unstable if it is not normalized. Thus, in this study, we modify a formula proposed in \([18]\) to calculate the gradient only under a given limited local area. Therefore, Eq. (3) can be modified as follows,

\[
E_{ext}(v) = -\frac{g_p}{\bar{g}} \sum_{p \in \Omega(v)} g(p) \frac{pv_i}{\|pv_i\|} + a' ,
\]

where

\[
g_p = [f_m * I(p) + D * I(p)] ,
\]

\[
\bar{g} = \frac{1}{W^2} \sum_{p \in \Omega(v)} g(p) ,
\]

where \( g_p \) is a gravity constant given by the user and \( \bar{g} \) is the mean gravity of the local area. The normalization form prevents the snake from diverging and oscillating, thereby causing the snake to update progressively. In addition, \( 'a' \) is a non-zero parameter for the distance effect on gravity, thereby avoiding a null solution of the denominator. To speed up the computation and reduce the convergent time, another external force is provided. By assuming that the initial curve is located above the desired boundaries, a vertical force which attracts the snake downward is added. Doing so avoids the noise effect, which occasionally occurs above the intimal layer and
within the sub-intima region. The noises attract the snake and, in doing so, deteriorate the results. The additional vertical force can attract the snake downward to identify the possible intima layer. Such a force that can not identify any layer in a short time interval is moved upward when the external force diminishes over time. In addition, the vertical force can accelerate the snake to identify the adventitial layer and reduce the noise effect of sub-intimal region simultaneously. To design this scheme, the additional force should be time-dependent. Herein, iteration time index is used as the time index. The vertical force is defined by

$$F_v = 0 \times \text{exp}(\text{index}/\text{Step})^\gamma,$$

where index is the iteration time index, and Step is a positive parameter to prolong or shorten the searching period. Based on experimental results, we recommend using Step=20 to identify intima and Step=100 while identify adventitia. Hence, Eq. (8) is modified to be

$$E_o(v_i) = -\frac{g}{\sum_{p \in \Omega_i}} \int [s_0 * I(p) + D_v * I(p) - \lambda(v) \sum_{p \in \Omega_i}] + a \gamma + \lambda v_i.$$

The fact that the echoes from different layers of different tissues are very close proximity to each other accounts for why the advential layer affects the snake in some areas when identifying the intima. This is particularly true if a larger window size is used. Window sizes ranging from 15x15 to 3x3 are applied for testing. The optimum window size is 9x9 for identifying intima and 7x7 for identifying adventitia based on some experiments. This choice also considers the processing time. For accelerating the computation and for reducing the possible noise effect, a diminishing window size with respect to the iteration times replaces the fixed window size design:

$$W_i = \text{int}(W_o \times \text{exp}(-\text{index}/\sigma))$$

where $W_i$ represents the original window size, index denotes the iteration time index and $\sigma$ is a positive value which acts as a diminishing factor. In addition, to reduce the effect from the noise layer while it is approaching a steady state, the gravity factor $a$ linearly increases via an iterative process. Based on these designs, the intimal and the adventitial boundaries of the far CCA wall can be detected without the noise and the sub-intimal region affecting it.

3. Results

Fig 1 illustrates a raw CCA B-Mode ultrasound image. Initially, the system automatically detects the spatial scale and, in doing so, the pixel size can be calculated. The user then needs to input the starting and ending points of the snake to identify the IMT. Thereafter, an initial contour identification procedure begins to identify an initial curve. The proposed algorithm is robust and noise-resistant, which is important since the real images unavoidably contain some noise in the artery lumen occasionally. Inability of the initial contour procedure to provide a robust mean for snakes might lead to failure of the results of snake or cause them to be time consuming. Herein, the initial curve produced by the identification procedure is used to identify the intima. According to those results, they are moved downward about 0.05 cm as initial curves to identify the adventitia. Owing to the anatomical structure of that, the intima-media complex thickness is at least about 0.05 cm in normal adults. Patients with cardiovascular diseases may have a thicker IMT; hence, searching from this position is preferred for the snake.

Fig. 4 presents the effect of the operator $D$ used in (3) which can remove the gradient resulting from the sub-intima region and enhance the gradient of intima and adventitia. Fig. 4(a) displays a portion of the raw image, Fig. 4(b) illustrates the raw image with its gradient image superimposed on it, and 4(c) summarizes the results of identifying intima and adventitia. Notably, for the gradient image in 4(b), the layer in the sub-intimal region no longer affects the gradient image. This phenomenon implies that the layer does not affect the snakes when identifying the intima or the adventitia. Instead, the gradient value in this layer might be negative for providing a repulsion force to push the snakes to the region of interest. Operator $D$ can also partially reduce the effect of the echoes in the IM complex while the IM complex is thick as depicted in Fig. 5. This feature facilitates the identification of the adventitia regardless of whether or not the IM complex is thick.

Fig. 5 depicts the relative thick IM complex in the bulb of a common carotid artery. The two ‘+’ symbols denote the starting and ending points as well. Fig. 6(a) shows a portion of the raw image, the gradient image of 6(a) in 6(b), and the result of snakes in 6(c). Fig. 6(a) and 6(b) obviously reveal that the noises exist above the intima. The noises in the IM complex might confuse the snakes while identifying the adventitia since the gradient may also produce a stable state for the snakes. However, based on our observation, the adventitial layers should provide a global minima for snakes. To avoid trapping the snake into a local minima, a cost function is defined and discussed in the next section.

To analyze the accuracy of our proposed snake, an experienced physician manually traced the boundaries of the intima and the adventitia five times in each case. In addition, this study also surveys many proposed snakes. The ziplock snake is suitable for our application and, therefore, is selected to implement for comparison. Figs. 7 summarize those results. Fig. 7(a) illustrates the raw image, 7(b) summarizes the results of our proposed snake, 7(c) displays the results of ziplock snake, and 7(d) depicts the mean contours of manual extraction performed five times. According to Fig. 7(c), an error occurs as denoted by an arrow. This error is owing to that ziplock snake traces the boundary from two ends given by the user. More specifically, if some noises are located in close proximity to the boundary of interest, the ziplock snake might move in a wrong direction. According to Fig. 7(a), there are layers in the IM complex as denoted by two arrows. These layers are closely attached to the adventitia.
so that its gradient value leads the ziplock snake in another direction, resulting in an error. Moreover, the ziplock snake takes much more time than the proposed snake in identifying the boundaries. However, those results are not shown here.

4. Discussion and Conclusion
While processing the CCA ultrasound B-Mode images, our results indicate that occasionally the intima-media complex is very thick. Therefore, the snakes cannot identify adventitia even if the additional time-diminishing vertical force is added. Our results further demonstrate that in some cases, there are some strong noises in the sub-intimal region. Therefore, a mechanism is added for solving these problems. A cost value, i.e., the mean gradient value of the current location of the snake, is calculated while the snake is identifying the adventitia. That is,

\[ J_f = \frac{1}{n} \sum_{i} g(v_i), \]

where \( g(v_i) \) denotes the gradient value where the snake element \( v_i \) is located. Notably, there is no square on function \( g(\cdot) \) since the gradient value may be negative which represents a repulsion force and should be avoided. Thus, we can prevent the snake from becoming trapped into the local minima due to some plaques on the artery wall. On the other hand, consider a situation in which the contrast between the sub-intima and the adventitia is not strong enough. Under this circumstance, it can remember the routes where it has passed by and memorize the shape with maximal cost. By this mechanism, the snake identifies the shape with maximal cost. By assuming that the adventitial layer should have the maximal mean gradient value between the sub-intimal region and a limited sub-adventitial region, the snake makes the results reliable. Fig. 5 illustrates an example with thick IMT. When the IMT is thick, it likely has some noises in the sub-intimal region. These noises might trap the snake and lead it to a local minimum. However, by memorizing the cost value, the snake can finally identify the optimum shape for the adventitia as indicated in Fig. 6(c).

Until now, our laboratory has processed thirty two images with a wide range of qualities such as images with a thin and thick IMT, with slight or strong noises. The system automatically processes the images, and it does not need manual correction. Herein, all of the results are confirmed and they are reliable based on our knowledge. The entire procedure for a single image analysis takes from 30 seconds to 1 minute, depending on the length of snakes and the IMT.

In conclusion, this study has developed an automatic system for detecting the intimal and the adventitial layers as the basis for calculating the IMT based on an active contour model. The Cohen’s snake is modified and some special criteria are added to obtain the global minima of the energy function so that the intimal and adventitial layer in the ultrasound images can be detected. In addition, the frequency view of the active model makes the divergence problem easy to control. This study also compares the proposed snake and the ziplock snake with respect to the manual extraction. According to our results, the proposed snake is more noise resistant than ziplock snake in this application. Thirty two wide-range qualities of the carotid artery ultrasound images are tested and the accuracy is high. We conclude that the results are reliable and acceptable, and they do not need any manual modifications. This novel automatic analysis system based on snake technique increases the reproducibility of the IMT measurement, i.e., an important predictor for heart infarction and strokes.

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References


Fig. 1: A raw B-Mode common carotid artery ultrasound image. The two ‘+’ marks denote the input points for the initial contour identification procedure given by the user. And the bright curve lies near the inner far carotid artery superimposed on the raw image is the result of initial contour identification.

Fig. 2: The intima-media (IM) complex contains the area between intima and adventitia. The sub-intima region may cause difficulties while in searching the adventitia due to the gradient value locate very near to the adventitia.

Fig. 3: The frequency response of the three normalized filters: the curve with ‘+’, ‘*’, and ‘o’ symbols denote the filters used in Cohen’s snake, the derived snake, and the high-pass filter, respectively.

Fig. 4: The effect of the sub-intima region. (a) denotes part of the raw image with IM complex. (b) shows the raw image with its gradient image superimposed on it, it is obvious that the gradient result from the sub-intima region has been removed by Eq. (3) and therefore it will reduce the difficulties of searching the adventitia. (c) denotes the result of the contour in searching intima and adventitia.

Fig. 5: This example shows that there is some noises locate near and above the intima, and the IM thickness is related large. There are also some noises existed in the IM complex.

Fig. 6: (a) is a part of a raw image as shown in Fig. 6, (b) is the gradient of (a), and (c) denotes the result of snakes. In (b), the two arrows show the local minima where the snake might be trapped.

Fig. 7: (a): A part of the raw image as shown in Fig. (1), (b): The result of the proposed snake, (c): The result of the ziplock snake, (d): The result of mean contour from 5 times of manual extraction.