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An integrated method for atherosclerotic carotid plaque segmentation in ultrasound image

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Background and objective: Carotid artery atherosclerosis is an important cause of stroke. Ultrasound imaging has been widely used in the diagnosis of atherosclerosis. Therefore, segmenting atherosclerotic carotid plaque in ultrasound image is an important task. Accurate plaque segmentation is helpful for the measurement of carotid plaque burden. In this paper, we propose and evaluate a novel learning-based integrated framework for plaque segmentation.
Methods: In our study, four different classification algorithms, along with the auto-context iterative algorithm, were employed to effectively integrate features from ultrasound images and later also the iteratively estimated and refined probability maps together for pixel-wise classification. The four classification algorithms were support vector machine with linear kernel, support vector machine with radial basis function kernel, AdaBoost and random forest. The plaque segmentation was implemented in the generated probability map. The performance of the four different learning-based plaque segmentation methods was tested on 29 B-mode ultrasound images. The evaluation indices for our proposed methods were consisted of sensitivity, specificity, Dice similarity coefficient, overlap index, error of area, absolute error of area, point-to-point distance, and Hausdorff point-to-point distance, along with the area under the ROC curve.
Results: The segmentation method integrated the random forest and an auto-context model obtained the best results (sensitivity $80.4 \pm 8.4\%$, specificity $96.5 \pm 2.0\%$, Dice similarity coefficient $81.0 \pm 4.1\%$, overlap index $68.3 \pm 5.8\%$, error of area $-1.02 \pm 18.3\%$, absolute error of area $14.7 \pm 10.9\%$, point-to-point distance 0.34 ± 0.10 mm, Hausdorff point-to-point distance 1.75 ± 1.02 mm, and area under the ROC curve 0.897), which were almost the best, compared with that from the existed methods.
Conclusions: Our proposed learning-based integrated framework investigated in this study could be useful for atherosclerotic carotid plaque segmentation, which will be helpful for the measurement of carotid plaque burden.

1. Introduction

The latest statistics from 2016 showed that stroke, a cardiovascular diseases, has become the fifth leading cause of death [1]. One of the important causes of stroke is atherosclerosis [2,3], which is a chronic disease. Atherosclerosis reduces the elasticity of the arterial walls and narrows the arteries [4], and it is characterized by plaque formation due to progressive intimal accumulation of lipids, protein, and cholesterol esters in the blood vessel wall [5]. Endarterectomy or stenting is the usual surgical procedure indicated by the stenosis of 70% or more [6]. However, many patients with large carotid plaque burden have no stenosis, i.e., carotid plaque burden is not the same as stenosis, because of compensatory enlargement of arteries [7]. Non-invasive and low-cost ultrasound imaging has been widely used in the diagnosis of cardiovascular diseases [8,9], including atherosclerosis. Therefore, accurate segmentation of atherosclerotic carotid plaque in the ultrasound image with the assistance of computer is an important task, which is helpful for the measurement of carotid plaque burden. Plaque burden measurement is useful for risk stratification, determination of treatment plan, genetic research and assessment of the effects of new therapies on atherosclerosis [3,10,11].

There are many studies related to atherosclerotic carotid plaque segmentation in ultrasound images. Two types of ultrasound images are used for plaque segmentation in the presented studies. One is transverse ultrasound images. For example, Abolmaesumi et al. [12] presented a fully automatic tracking and segmentation

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system for extracting CCA boundaries from transverse ultrasound images in real time. In [13], a modified Star-Kalman approach was proposed by Guerrero et al. to determine vessel contours and ellipse parameters. Ukwatta et al. [14] described a 3D algorithm based on a modified sparse field level set algorithm to segment plaque, which yielded high-accuracy and high-repeatability. Aside from transverse ultrasound images, another type of ultrasound image used for plaque segmentation is longitudinal ultrasound image. Hamou et al. [15] proposed a method based on the histogram equalization and Canny edge detection algorithms to detect the plaque regions in longitudinal 2D CCA ultrasound images. Abdel-Dayen et al. [16] used a morphological approach for the carotid contour extraction from longitudinal ultrasound images of the CCA. Four different snake models (Balloon, gradient vector flow (GVF), Lai & Chin, William & Shah), with initialization based on Doppler blood flow images, were used and evaluated for segmenting plaque in longitudinal ultrasound images by Loizou et al [17].

In addition to the distinctions among the types of ultrasound images used in these presented studies, there is a difference in the automaticity of the existing methods. Among the aforementioned methods, some are semi-automatic, such as that in [14]. Indeed, in recent decades, many semi-automatic methods were validated for plaque segmentation. Gill et al. [18] proposed a semi-automatic segmentation method to track the progression of atherosclerotic plaque in three-dimensional (3D) images of the carotid artery by introducing the balloon model [19]. Cardinal et al. [20] used a semi-automatic intravascular ultrasound (IVUS) segmentation model to segment the lumen, intima-media thickness, and plaque in parallel with a fast-marching approach. A semi-automated method was proposed by Buchanan et al. [21] to measure the 3D ultrasound plaque. Destrempes et al. [22] segmented plaques in the sequences of B-mode ultrasound images using the Bayesian model combined with the manual starting point segmented in the first frame. They tested their proposed segmentation method on 94 sequences of 33 patients (for a total of 8988 images), and obtained a mean point-to-point distance of 0.24 ± 0.08mm, together with a Hausdorff distance of 1.24 ± 0.40mm.

Furthermore, automatic and robust segmentation of atherosclerotic carotid plaque in ultrasound images has attracted more researchers. Other than the methods presented in [12,17], other automatic algorithms were also proposed in succession. In [23], the Hough transform was applied to perform plaque segmentation in four 2D cross-sectional ultrasound images. Considering the complex structure and heterogeneity of plaques, Cheng et al. [24] introduced a fully automatic algorithm based on a hybrid level-set framework to outline carotid plaques in 3D ultrasound images by making use of the prior knowledge of the media adventitia boundary and lumen intima boundary. In [25], a fully automated methodology integrating the graphical models and Markov random fields was proposed to identify the plaque region by Gastounioti et al. In fact, ultrasound imaging techniques contain many other types, such as color Doppler, contrast-enhanced ultrasound (CEUS), and so on [26]. In [17], researchers established initialization on color Doppler blood flow images. Akkus et al. [27] were the first to introduce the method for carotid plaque segmentation by exploiting the combined information from simultaneously acquired B-mode ultrasound and CEUS images. Their proposed method comprised several processing parts that contained non-rigid motion estimation and compensation, vessel detection, and plaque segmentation.

In a word, the superiority of ultrasound imaging rests in the computer-aided diagnosis (CAD) of carotid plaque; however, ultrasound B-mode imaging presents several difficulties due to some typical image characteristics, such as low contrast, speckle noise, echo shadows and artifacts, which usually leads to poor quality images that require the interpretation of an expert [8]. As described in [28], speckle is a multiplicative noise in ultrasound imaging. If the mathematical models (i.e., snake model [17], level set [14,24], and balloon model [18,19]) are used for plaque segmentation, a denoising algorithm is necessary, which requires prior knowledge regarding the type of the speckle noise, the distribution of the speckle noise, etc. Fortunately, learning-based algorithms can be robustly used for the images with noise and artifacts, et al [29,30].

Although most of the proposed atherosclerotic carotid plaque segmentation methods have achieved satisfactory performance, there are some limitations and areas for improvement. (1) Some articles describe carotid segmentation techniques only of the walls and not of the plaque itself [12,13,16,18,23]. (2) A few existing methods require careful initialization, and often require careful parameter tuning for convergence [14,17,24]. (3) Some of the proposed methods, especially semi-automatic methods, require a certain amount of manual operations, which introduce operator variability [21,22]. (4) In [17,27], the fully automatic plaque segmentation methods, combining different modalities of ultrasound image, are presented. These methods require that the imaging devices record the different modalities of ultrasound images simultaneously, or the image registration techniques are employed between different modalities of images.

To overcome the difficulties inherent in ultrasound images and to improve the limitations of the existing methods, in this paper, we introduce an integrated framework to semi-automatically segment atherosclerotic carotid plaque in the B-mode longitudinal ultrasound image. Our proposed method, integrating learning-based algorithms and an auto-context model [31,32], consists of region of interest (ROI) extraction, plaque ROI candidate identification and plaque segmentation. We have validated our proposed method on 29 patient subjects and obtained promising performance.

2. Database

In our work, all the data are open resource and were made available by Loizou et al. [17,28] on the social networking site Research Gate. For the convenience of the reader, we describe the database repeatedly.

2.1. Dataset introduction

The database contains a total of 80 B-mode and blood flow longitudinal ultrasound images of the CCA, the normalized images of the atherosclerotic carotid plaques and the manual delineated images, as well as Doppler color ultrasound images (which are not used in our method). Only 29 patient subjects can be used in our study, however, due to the presence of duplicate images, which may be the result of the loss of other images in the transmission or storage process. All the images were acquired using an ATL HDI-3000 ultrasound scanner (Advanced Technology Laboratories, Seattle, USA) and were recorded digitally on a magneto optical drive with a resolution of 768 × 576 pixels with 256 Gy levels. Digital images were resolution-normalized at 16.66 pixels/mm (see Section II-C in [17]). The images were recorded at Saint Mary's Hospital, Imperial College of Medicine, Science and Technology, U.K., from 29 symptomatic patients. These patients were at risk of atherosclerosis and had already developed clinical symptoms such as a stroke or a transient ischemic attack. The degree of carotid artery stenosis of the interrogated subjects was 50.59 ± 21.26% with the North American Symptomatic Carotid Endarterectomy Trial (NASCET) formula ($r = (1 - D_1/D_2) \times 100$) or 66.81 ± 11.91% by the European Carotid Surgery Trial (ECST) formula ($r = (1 - D_1/D_3) \times 100$). r represents the degree of carotid artery stenosis. D_1 is the narrowest internal carotid artery (ICA) diameter, and D_2 diameter normal distal cervical ICA. The estimated original diameter at the site of the stenosis is denoted as D_3 [33].