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● *Original Contribution*

A FULLY-AUTOMATIC METHOD TO SEGMENT THE CAROTID ARTERY LAYERS IN ULTRASOUND IMAGING: APPLICATION TO QUANTIFY THE COMPRESSION-DECOMPRESSION PATTERN OF THE INTIMA-MEDIA COMPLEX DURING THE CARDIAC CYCLE

Guillaume Zahnd,[*] Kostas Kapellas,[†] Martijn van Hattem,[‡] Anouk van Dijk,[‡] André Sérusclat,[§] Philippe Moulin,[||] Aad van der Lugt,[‡] Michael Skilton,[¶] and Maciej Orkisz[#]

[*]Biomedical Imaging Group Rotterdam, Departments of Radiology & Nuclear Medicine and Medical Informatics, Erasmus MC, University Medical Center Rotterdam, Rotterdam, The Netherlands; [†]Australian Research Centre for Population Oral Health, School of Dentistry, University of Adelaide, Adelaide, Australia; [‡]Department of Radiology, Erasmus MC, University Medical Center Rotterdam, Rotterdam, The Netherlands; [§]Department of Radiology, Louis Pradel Hospital, Hospices Civils de Lyon, Université Lyon 1, Lyon, France; [||]Department of Endocrinology, Louis Pradel Hospital, Hospices Civils de Lyon, Université Lyon 1, Lyon, France; [¶]Boden Institute of Obesity, Nutrition, Exercise and Eating Disorders, University of Sydney, Sydney, Australia; and [#]Univ Lyon, INSA-Lyon, Université Lyon 1, UJM-Saint Etienne, CNRS, Inserm, CREATIS UMR 5220, U1206, F-69621, Lyon, France

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Abstract—The aim of this study was to introduce and evaluate a contour segmentation method to extract the interfaces of the intima–media complex in carotid B-mode ultrasound images. The method was applied to assess the temporal variation of intima–media thickness during the cardiac cycle. The main methodological contribution of the proposed approach is the introduction of an augmented dimension to process 2-D images in a 3-D space. The third dimension, which is added to the two spatial dimensions of the image, corresponds to the tentative local thickness of the intima–media complex. The method is based on a dynamic programming scheme that runs in a 3-D space generated with a shape-adapted filter bank. The optimal solution corresponds to a single medial axis representation that fully describes the two anatomical interfaces of the arterial wall. The method is fully automatic and does not require any input from the user. The method was trained on 60 subjects and validated on 184 other subjects from six different cohorts and four different medical centers. The arterial wall was successfully segmented in all analyzed images (average pixel size = 57 ± 20 mm), with average segmentation errors of 47 ± 70 mm for the lumen–intima interface, 55 ± 68 mm for the media–adventitia interface and 66 ± 90 mm for the intima–media thickness. The amplitude of the temporal variations in IMT during the cardiac cycle was significantly higher in the diseased population than in healthy volunteers (106 ± 48 vs. 86 ± 34 mm, $p = 0.001$). The introduced framework is a promising approach to investigate an emerging functional parameter of the arterial wall by assessing the cyclic compression–decompression pattern of the tissues. (E-mail: zahnd-guillaume@is.naist.jp) **© 2016 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Contour segmentation, Carotid artery, Ultrasound, Dynamic programming, Front propagation, Intima–media thickness.**

INTRODUCTION

Cardiovascular diseases are the leading cause of mortality and morbidity worldwide (World Health Organization [WHO] 2015). An early sign of the atherosclerotic process is arterial wall thickening. Carotid intima–media thickness (IMT) (Fig. 1) has been reported to be strongly correlated with cardiovascular diseases (Baldassarre et al. 2000; O'Leary et al. 1999; Polak et al. 2011), and is considered an established biomarker of atherosclerosis (Lorenz et al. 2007): IMT values < 1.1 mm indicate a healthy artery (Jarauta et al. 2010), values > 1.5 mm are a surrogate marker for an atherosclerosis plaque (Touboul et al. 2012) and transitional values define an intermediate risk. Therefore, assessing IMT is crucial to evaluation of cardiovascular risk. The focus of the present study is the assessment of IMT at an early stage of atherosclerosis, in images without atheromatous plaque.

Address correspondence to: Guillaume Zahnd, Imaging-based Computational Biomedicine (ICB) Lab, Graduate School of Information Science, Nara Institute of Science and Technology (NAIST), Osaka, Japan E-mail: zahnd-guillaume@is.naist.jp

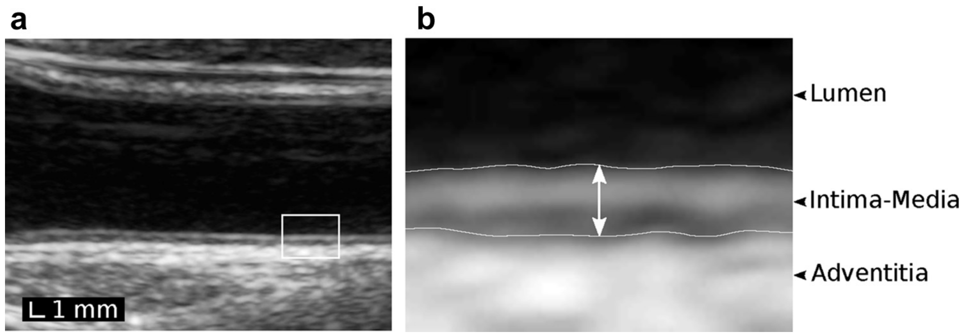

Fig. 1. (a) Longitudinal view of the common carotid artery in B-mode ultrasound imaging. (b) Enlarged region detailing the intima–media complex. The lumen–intima and media–adventitia interfaces are represented by the contour lines, and intima–media thickness is indicated by the *arrow*.

B-Mode ultrasound (US) imaging has been extensively used to assess carotid IMT *in vivo*. The problem of quantifying IMT is generally addressed by extracting the two contours of the intima–media complex, that is, the lumen–intima (LI) and media–adventitia (MA) interfaces (Fig. 1), and calculating the distance between these two contours. According to the Mannheim consensus (Touboul et al. 2012), the far wall of the artery is generally analyzed, mainly because of better depiction of the intima–media double-line pattern, as well as possible overestimation of the IMT in the near wall (Skilton et al. 2011). A large number of computerized segmentation methods have been proposed to (semi-) automatically extract the LI and MA interfaces in 2-D US images. Recent comprehensive review articles (Ilea et al. 2013; Loizou 2014; Molinari et al. 2010) propose categorizations of these methods according to image-processing techniques used, and provide their synthetic description together with main and other results. Hereafter, we cite only examples of major studies.

Let us note that the interfaces of interest may be extracted either sequentially or simultaneously. Most of the existing methods fall in the broad category of sequential contour extraction; that is, the two contours are extracted more or less independently (sometimes one extracted contour is used as initialization to extract the second) and then possibly refined to improve their spatial consistency. Among these approaches, methods based on feature extraction and region classification have been recommended for extraction of the pixels that belong to the intima–media complex (Menchón-Lara et al. 2014; Molinari et al. 2011). An edge operator based on statistical filtering has been introduced to extract the anatomical boundaries by analyzing the local statistics of the image (Faita et al. 2008). A method based on adaptative thresholding followed by a morphologic operation was proposed to detect the contours of the layers (Ilea et al. 2013). Various implementations of the active-contour framework have been put forward by different teams (Bastida-Jumilla et al. 2015; Cheng et al. 2002; Loizou et al. 2007; Mao et al. 2000; Xu et al. 2012). Dynamic programming methodology has also been adopted in combination with various techniques, such as fuzzy expression forms representing image features and geometric characteristics of vessel–wall interfaces (Liang et al. 2000), smooth intensity thresholding surfaces and geometric snakes (Rocha et al. 2010) and directional Haar-like filter (Lee et al. 2010).

Cheng and Jiang (2008) proposed a dual-dynamic-programming method controlling the simultaneous evolution of two curves and devised to jointly extract both contours of the intima–media complex. They argued that their approach was able to robustly cope with noise and irregular contrasts. In particular, they maintained that dual dynamic programming was more efficient in handling the spatial consistency of the contours than traditional dynamic programming, where the contours, extracted sequentially, may intersect or collapse onto each other. Following a similar strategy, we have developed a method (Zahnd et al. 2012, 2013b) based on a representation known as *medial axis*, that is, a single object fully describing the two contours of the intima–media complex by means of (i) the radial *position* of a curve located midway between LI and MA interfaces, and (ii) the local *distance* between each contour and this curve. That information was separately estimated in each column of the image by means of a shape-adapted filter bank. The algorithm processed a whole image sequence (hereafter referred to as *cine loop*) after an interactive initialization performed in the first frame. The method efficiently controlled the location and smooth shape of the central curve, but could not guarantee the smoothness of the contours.

Overall, accuracy of the methods reported by the above-cited studies, in IMT quantification, as well as in both LI and MA interface extraction, ranged between 10 and 90 μm. Nevertheless, these results were obtained using different images, distinct reference annotations and