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Freehand three-dimensional ultrasound imaging of carotid artery using motion tracking technology

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ABSTRACT

Ultrasound imaging has been extensively used for determining the severity of carotid atherosclerotic stenosis. In particular, the morphological characterization of carotid plaques can be performed for risk stratification of patients. However, using 2D ultrasound imaging for detecting morphological changes in plaques has several limitations. Due to the scan was performed on a single longitudinal cross-section, the selected 2D image is difficult to represent the entire morphology and volume of plaque and vessel lumen. In addition, the precise positions of 2D ultrasound images highly depend on the radiologists' experience, it makes the serial long-term exams of anti-atherosclerotic therapies are difficult to relocate the same corresponding planes by using 2D B-mode images. This has led to the recent development of three-dimensional (3D) ultrasound imaging, which offers improved visualization and quantification of complex morphologies of carotid plaques. In the present study, a freehand 3D ultrasound imaging technique based on optical motion tracking technology is proposed. Unlike other optical tracking systems, the marker is a small rigid body that is attached to the ultrasound probe and is tracked by eight high-performance digital cameras. The probe positions in 3D space coordinates are then calibrated at spatial and temporal resolutions of 10 μm and 0.01 s, respectively. The image segmentation procedure involves Otsu's and the active contour model algorithms and accurately detects the contours of the carotid arteries. The proposed imaging technique was verified using normal artery and atherosclerotic stenosis phantoms. Human experiments involving freehand scanning of the carotid artery of a volunteer were also performed. The results indicated that compared with manual segmentation, the lowest percentage errors of the proposed segmentation procedure were 7.8% and 9.1% for the external and internal carotid arteries, respectively. Finally, the effect of handshaking was calibrated using the optical tracking system for reconstructing a 3D image.

1. Introduction

Atherosclerotic lesions in the carotid artery are the most common type of cardiovascular disease, which is the leading cause of strokes [1]. Carotid atherosclerosis occurs because of the gradual accumulation of fatty acid deposits, calcium carbonate, and cholesterol in the intima-media of the carotid arteries, and it results in the formation of plaque, which eventually leads to carotid artery stenosis and format thrombosis [2]. Therefore, accurate measurement and understanding of the geometry of carotid arteries are crucial for evaluating the risk of ischemic stroke. Currently, several noninvasive imaging modalities are employed to obtain morphological images of carotid arteries for diagnosing carotid artery stenosis, including magnetic resonance angiography, computed tomography angiography, and ultrasound. Among these, ultrasound not only provides accurate morphological information on carotid artery stenosis but is also safe and faster.

Conventional two-dimensional (2D) ultrasound imaging has been widely used to measure the intima-media thickness [3,4] and obtain the plaque morphology [5] of stenotic carotid arteries on the basis of a single longitudinal view. Furthermore, for long-term monitoring of anti-atherosclerotic therapies, it is difficult to relocate the plaque by using B-mode image. However, three-dimensional (3D) ultrasound imaging can not only reveal the surface irregularities, geometry, and distribution of plaques during atherosclerosis progression and regression but also provide information about the plaque's response to therapy [6–8]. Since ultrasound imaging of carotid arteries requires a scanning length of at least 4 cm, most 3D carotid artery images are reconstructed from a series of 2D ultrasound images obtained using a

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one-dimensional (1D) array probe. Typically, the effectiveness of 3D reconstruction technologies depends on the effectiveness of ultrasound image segmentation and accurate ultrasound probe calibration. Calibration is required for accurate mathematical transformation (rotation, translation, and scaling), which is performed for converting the 2D coordinates of a pixel in ultrasound images into 3D coordinates in the reference frame [9]. Several tracking systems, such as mechanical, acoustic, electromagnetic, and optical tracking systems, have been used to calibrate ultrasound probes for locating the positions and orientations of 2D images within a volume [10]. Although mechanical scanners can accurately locate the position of the probe, the method involved is cumbersome. Acoustic methods involve generating acoustic waves and detecting them by using microphones. However, acoustic tracking systems are affected by variations in the temperature, pressure, and humidity because these parameters affect the propagation speed of sound in air. In electromagnetic tracking systems, a magnetic field sensor placed on a probe measures electrical currents induced during the motion of the probe in a magnetic field generated by a transmitter. However, electromagnetic tracking systems have a disadvantage: signals from sources such as power cables and surrounding instruments interfere with the tracking system signals, affecting the tracking accuracy. Therefore, it is challenging to use electromagnetic tracking systems in an operating room where various metallic objects are moved around in the magnetic field generated by the transmitter.

The most widely used calibration technology for freehand 3D ultrasound imaging is an optical tracking system involving markers distributed on a rigid structure and multiple cameras. The motion of the probe in all six degrees of freedom is tracked to obtain its position and orientation [11–13]. Currently, two commercial optical trackers are commonly used for medical navigation or 3D ultrasound imaging: Polaris (two cameras) and Optotrak (three cameras); both are manufactured by Northern Digital (Toronto, Canada). These optical trackers can accurately track the ultrasound probe. However, a problem is that physicians find the large rigid structure of the marker on the probe inconvenient during examination. For instance, the diameter of a marker is approximately 11 mm (typically four markers are required on the rigid body), and the minimum passive marker spacing is approximately $50\ \text{mm} \times 60\ \text{mm}$ [11,13]. Another problem is that the rigid body should face a camera during motion because of the use of only two or three cameras. Nevertheless, these disadvantages can be overcome by using additional high-performance cameras during ultrasound examination.

In addition to accurate probe calibration, another critical factor in 3D ultrasound image reconstruction is effective ultrasound image segmentation, which can facilitate distinguishing the lumen, inner vessel wall, plaque area, and outer vessel wall in grayscale images, thereby clarifying the correct contours of the atherosclerotic lesions in the artery. Several studies have proposed algorithms for carotid artery boundary detection. For instance, the spokes ellipse algorithm was used to detect the carotid artery boundary [14]; however, this algorithm is based on the assumption that the carotid artery cross section is elliptical, and in addition, a sudden movement of the probe may disrupt the tracking [15]. Thus, the algorithm is not completely applicable to 3D ultrasound imaging of carotid artery stenosis. Furthermore, the star algorithm was used for tracking the carotid artery in real time [16]. Guerrero et al. proposed a Star–Kalman algorithm that involves a Kalman filter and an elliptical vessel model for determining the vessel boundary and estimating ellipse parameters; the algorithm can be used for quickly calculating the transverse area [17]. However, determining the carotid model parameters for fitting is difficult when using this algorithm. Hough transform (HT) can be used for combining the intensity threshold with template matching in an edge detection algorithm [18]. The greatest advantage of the HT algorithm is its ability to estimate the intima-media thickness, but it is not suitable for detecting the edges of a carotid artery in all situations because the carotid artery boundary has a random shape. In addition to the aforementioned methods, an active contour model (ACM) algorithm was successfully used for medical image segmentation; the contour location was determined by balancing the forces obtained from processed image data and the counteracting local constraints. Mao et al. comprehensively evaluated the performance of an interactive segmentation algorithm based on a dynamic contour model by applying it to an ultrasound carotid artery image [19]. Furthermore, a different type of ACM algorithm—a geometrically deformable model algorithm—was proposed for application to 3D carotid ultrasound images by Zahalka and Fenster [20]. Ukwatta et al. proposed a carotid artery segmentation algorithm based on the concept of ACM for 3D ultrasound imaging [21,22]. However, this algorithm requires manual segmentation, thus enabling the direct measurement of the semiautomatic manual procedure. On the other hand, many algorithms as well as ACM have been proposed for carotid artery segmentation for both 2D and 3D ultrasound images. A semiautomatic segmentation algorithm based on distance regularized level set evolution method was used for measuring the vessel wall volume of the carotid artery using 3D ultrasound images [23,24]. This method segments outer wall and lumen intima boundaries of carotid artery, but the manual initialization of the boundary points is still required. Surface graph cuts based algorithm was proposed for segmenting carotid artery lumen from free-hand ultrasound images [25]. The method reduced the complication of manual initialization, however, lower accuracy (Dice Similarity Coefficient of 67%) of segmentation results were obtained. Active Shape Model was proposed to segment the lumen-intima and the media-adventitia boundaries of the carotid artery, but it was only used for the common carotid artery [26].

The objective of the present study was to develop a contour detection procedure for carotid atherosclerosis for obtaining effective contours from ultrasound images and to transform the coordinates of a tracking device in the global coordinate system into those in the image coordinate system for accurate freehand 3D ultrasound image reconstruction. The optical tracking system used involved eight high-performance digital cameras that facilitated detecting the motion of a small rigid body (which served as the marker and was attached to the ultrasound probe) with high spatial and temporal resolutions of 10 μm and 0.01 s, respectively. Finally, freehand scanning of 3D ultrasound images obtained from phantom experiments and human examination was performed.

2. Materials and methods

2.1. Experimental setup

All recordings in the phantom and human experiments were made using a Terason t3000 scanner (Teratech Corporation, MA, USA) with a multifrequency transducer (12L5). When the transducer was moved during freehand scanning, the B-mode images were digitized at a frame rate of 26 fps. A 3D motion tracking system (Motion Analysis Corporation, Santa Rosa, CA, USA) with eight Eagle digital CCD cameras and four passive fluorescent markers (each marker had a diameter of 2 mm and the distance between two markers was approximately 4–5 mm) was used to collect kinematic data and is shown in Fig. 1. The markers were fixed on the probe firmly by twin adhesive. When a target is visible in two or more camera views, sufficient information is available to track the target in a 3D space. Generally, two and three cameras are sufficient to track the target in 3D space. Eight cameras are the