Computerized Medical Imaging and Graphics 38 (2014) 123–136

Contents lists available at ScienceDirect

Computerized Medical Imaging and Graphics

journal homepage: www.elsevier.com/locate/compmedimag

A local angle compensation method based on kinematics constraints for non-invasive vascular axial strain computations on human carotid arteries

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ARTICLE INFO

Article history:
Received 1 October 2012
Received in revised form 28 June 2013
Accepted 7 August 2013

Keywords:
Ultrasound elastography
Carotid artery
Strain tensor
Angle-dependence
Strain rate
Healthy carotids
Atherosclerotic plaques
Vulnerable carotid plaques

ABSTRACT

Non invasive vascular elastography (NIVE) was developed to highlight atherosclerotic plaque constituents. However, NIVE motion estimates are affected by artifacts, such as an underestimation of deformations due to projected movement angles with respect to the ultrasound beam, movements of the operator or of the patient during image acquisition. The main objective of this work was to propose a local angle compensation method within small measurement windows for the axial strain based on kinematics constraints, and to introduce a filtering process on the strain time-varying curve to reduce as much as possible the impact of motion artifacts. With such preprocessing, we successfully quantified the strain behavior of near and far walls in longitudinal images of internal carotid arteries without ($n = 30$) and with ($n = 21$) significant atherosclerotic disease (greater than 50% stenosis). Maximum strain rates of 4.49% s^{-1} for the healthy group and of 2.29% s^{-1} for the atherosclerotic group were calculated on the far wall of internal carotid arteries; significant differences were found between these values ($p = 0.001$). The minimum strain rates, also on the far wall of internal carotid arteries, of −3.68% s^{-1} for the healthy group and of −1.89% s^{-1} for the atherosclerotic group were significantly different as well ($p = 8 \times 10^{-4}$). The mean systolic, diastolic and cumulated axial strains could also distinguish the two groups after normalization by the pressure gradient between acquired images. To conclude, the proposed techniques allowed to differentiate healthy and atherosclerotic carotid arteries and may help to diagnose vulnerable plaques.

1. Introduction

Stroke is the third leading cause of death and the first cause of morbidity in western countries [1]. Mainly due to atherosclerosis, 60% of all cerebral infarctions are linked to the rupture of a vulnerable plaque [2]. Carotid stenosis has long been the primary marker of vulnerability. However, it has been shown that calcified plaques are less prone to rupture than non calcified plaques [3] and are thus more stable. A vulnerable plaque can be characterized by a soft necrotic core embedded in the wall under a thin fibrous cap [4]. In fact, plaque vulnerability is multifactorial and depends mainly on its tissue composition (fibrotic, calcified and lipidic) and the biomechanical properties of its components. The studies [5,6], and later [7,8], have shown that circumferential stress, more specifically the “peak cap stress” (PCS), is a strong mechanical indicator of vulnerability. The PCS mainly depends on the fibrous cap thickness, lipid core Young modulus and blood pressure. In this context, it is relevant to assess plaque morphology, composition and biomechanical properties to prevent stroke events. Mechanical properties of the arterial wall have been the subject of numerous researches and various tools have been developed using ultrasound imaging to measure compliance, distensibility, stiffness [9–12], and elasticity [13–17].

Elastography is an ultrasound imaging technique for estimating elastic properties of tissues [18]. It has been extensively studied for the diagnosis of breast, liver, prostate and thyroid [17]. In the context of diagnosis of arterial vascular diseases, the pioneer work in intravascular elastography by [19–22] using intravascular ultrasound (IVUS) catheter has shown the ability to distinguish between fiber, fibro fatty and fatty plaque components based on the radial

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http://dx.doi.org/10.1016/j.compmedimag.2013.08.005

strain. Later, different components of the full strain tensor were proposed and studied [23–32] in the context of human coronary and carotid arteries. More recently, IVUS elastography has led to a promising tool known as modulography [13,16,33–38], which aims at computing the Young modulus mapping of the arterial wall. Although IVUS imaging provides a higher spatial resolution than external echography, the main modality used for superficial vessels, such as the carotid artery, is external echography due to its non-invasiveness. Elastography studies have been performed on human carotid arteries using cross-correlation algorithms [39–42] and the Lagrangian speckle model estimator (LSME) [43–46], which allows the computation of the complete 2D strain tensor. Thus, the LSME gives access from a single optimization to axial and lateral strains and shears. These studies have shown a potential for non-invasive vascular elastography (NIVE) to evaluate arterial stiffness and plaque morphology based on strain and shear maps. In both IVUS and NIVE elastography, the natural pulsation of the blood flow induces vessel motion and deformation, which are detected by ultrasound speckle tracking applied on either B-mode or radio-frequency (RF)-mode data.

Noninvasive vascular imaging techniques still present challenges. Due to the low lateral resolution of external echography using standard beamforming, the lateral components of the displacement gradient matrix are less reliable than the axial ones [47–49], thus limiting the evaluation of the strain tensor to the axial strain and shear components. In this context, one would prefer a longitudinal analysis of the artery to a cross-sectional one, since displacements and deformations will then mainly occur in the axial direction. Moreover, it has been shown, with IVUS elastography [50,51] and NIVE [52], that the strain tensor depends on the coordinate system and needs to be corrected for a reliable interpretation. In IVUS, due to the catheter eccentricity, the strain tensor needs to be transformed towards the vessel coordinate system. Similarly, in external elastography, the strain tensor can be compensated for the local wall deformation direction.

The first goal of this paper is to provide a new local compensation method based on the plane strain condition in the context of NIVE. Previous angle correction methods for the strain estimate were presented to obtain a compounded strain image or to determine the normal strain tensor, in the context of beam-steered data [53–57]. However, the beam-steering approaches consider angles (for each direction of the beam-steering) that are global to the image. As far as we know, this is a difference with our proposed angle compensation method, where the angle is computed locally on measurement windows. The effect of the angle compensation on the axial strain time-varying curves was also investigated. Moreover, the resulting temporal strain rate evolution – a parameter that was previously described for cardiac strain application [58–64] – is presented and discussed in this work. In order to compute the strain rate, a filtering method that keeps the principal frequency components close to the heartbeat frequency is introduced. It is shown that the strain rate computed on the filtered axial strain curves is able to differentiate normal from atherosclerotic carotid walls, with or without the angle compensation.

2. Materials and methods

With the database described next, we propose pre-processing steps to optimize the reliability of axial strain estimates. The scheme first requires an initialization followed by an automatic segmentation of all frames of a video RF-mode sequence of the carotid artery; the computation of the elastogram within the segmented region of all frames; the determination of the time-varying mean strains within the segmented region; the angle compensation of mean strain values; the bandpass filtering of time-varying mean strain curves; and the extraction of quantitative structural parameters for diagnostic purpose. These pre-processing steps are described below.

2.1. Recruitment of participants

All subjects signed a written informed consent form approved by the ethical committee of the University of Montreal Hospital Research Center. Fifteen healthy subjects had no sign of carotid plaque and they had no history of cardiovascular or cerebrovascular diseases. Seven women and eight men, ranging in age from 41 to 71 years, constituted the healthy group. The atherosclerotic group diagnosed with a carotid stenosis of at least 50% in diameter reduction was composed of 4 women and 17 men, for a total of 21 patients, aging from 56 to 80 years old. Since one of the objectives of this study was to propose a compensation method to correct axial strain distributions for both near and far walls,[1] we have only selected patients for which one of the internal carotid arteries exhibited a plaque on both near and far walls of the vessel.

2.2. Data acquisition

To identify the carotid plaque, the first step of the acquisition process consisted of a conventional duplex B-mode and echo Doppler examination with a Philips 5000 system (Philips Medical Systems, Bothell, WA, USA). As shown in Fig. 1, Doppler scan helps locating hypoechoic plaques, which can be difficult to see in conventional B-mode examination. Next, RF data were recorded with a Sonix RP scanner (Ultrasonix, Vancouver, BC, Canada) using a 10 MHz frequency transducer (model L14-5/38, 128 elements, 7.2 MHz center frequency with a fractional bandwidth of 70% at −6 dB) with a sampling frequency of 40 MHz. The nominal center frequency was around 5.2 MHz on the RF data due to the high-frequency tissue attenuation. The RF acquisition frame rate varied from 16 to 42 images per second according to the depth of field of the RF images (based on the location of the wall or plaque). For the 15 subjects with healthy carotids, both carotids were imaged (left and right). For the 21 patients, the image was acquired on the side of the plaque.

2.3. Image segmentation

Longitudinal image sequences of a few seconds of the internal carotid artery were segmented using semi-automatic methods described elsewhere [65,66]. Healthy subject sequences were treated with the algorithm described in [65]. This algorithm performs the segmentation of the intima-media thickness (IMT) using prior knowledge on the size of the human IMT and a likelihood based on mixtures of Nakagami distributions used to describe first order statistics of the RF echo envelope. In this context, the IMT refers to the intima-media complex, with boundaries made of the lumen-intima and media-adventitia interfaces. The statistical parameters of the mixtures of Nakagami distributions were estimated using an Expectation-Maximization algorithm [67]. The segmentation of the IMT (for healthy vessel walls) is viewed as the maximum a posteriori (MAP) of a Bayesian model, which was computed with a stochastic optimization algorithm. This semi-automatic segmentation method requires a user to manually select 3–5 points within the IMT on a single (arbitrary) reference frame. It was demonstrated in [65] on a database of 30 sequences of ultrasonic B-mode images of presumably disease-free control subjects

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[1] Near and far walls of the carotid artery are defined with respect to the probe position.