Ultrasound in Med. & Biol., Vol. 39, No. 7, pp. 1168–1177, 2013

0301-5629/$ - see front matter

http://dx.doi.org/10.1016/j.ultrasmedbio.2013.01.018

● *Original Contribution*

AXIAL AND RADIAL WAVEFORMS IN COMMON CAROTID ARTERY: AN ADVANCED METHOD FOR STUDYING ARTERIAL ELASTIC PROPERTIES IN ULTRASOUND IMAGING

Heikki Yli-Ollila,*† T. Laitinen,†‡ M. Weckström,* and T. M. Laitinen†

*Department of Physics, Biophysics and Biocenter Oulu, University of Oulu, Finland; †Department of Clinical Physiology and Nuclear Medicine, Kuopio University Hospital, Finland; and ‡Department of Clinical Physiology and Nuclear Medicine, University of Eastern Finland

(*Received* 25 *May* 2012; *revised* 1 *November* 2012; *in final form* 27 *January* 2013)

Abstract—Our objective was to develop a method for studying the biomechanics of the common carotid artery (CCA) by evaluating both radial and less known axial distension of the arterial wall. We developed software capable of tracking the movements of different arterial wall layers from ultrasound recordings of CCA, and we then calculated several indices of arterial stiffness. The wide spectrum of arterial stiffness indices defined from one measurement is a unique feature of our method. The motion-tracking algorithm is based on 2-D cross-correlation enhanced with luminance optimizations. The repeatability and reproducibility of the motion tracking were evaluated by performing 10-s ultrasound recordings of left CCA twice to 19 healthy volunteers (11 women, 8 men, age 41.3 ± 14.3 y). The method revealed a biphasic axial movement of the CCA and demonstrated that the indices of arterial stiffness defined from radial movement of carotid artery are reproducible (Cronbach's α, 0.59–0.97) as well as the indices from axial movement are reproducible (Cronbach's α, −0.68 to 0.93). The good reproducibility of the motion tracking is evidence that this method of studying arterial elastic properties is adequate for *in vivo* studies. (E-mail: heikki.yli-ollila@kuh.fi) © 2013 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Axial distension, Radial distension, Hemodynamics, Arterial stiffness, Common carotid artery, Motion tracking.**

INTRODUCTION

Cardiovascular diseases are the main cause of death in the Western world. The stiffening process of the arteries starts from the infancy and continues throughout a lifetime (Raitakari et al. 2005). Many diseases and unhealthy lifestyle habits (*e.g.*, tobacco) smoking accelerates the vascular calcification process (Lee et al. 1997; Raitakari et al. 2003). Most of the current techniques for measuring vascular health either ineffective to detect the pre-clinical changes in the arterial wall, too time consuming or expensive to be conducted on a larger population, expose the patient to ionizing radiation, or require an invasive procedures that can cause inflammations and other adverse effects. There is a need for a method that can be used to study pre-clinical atherosclerosis in large populations.

The radial distension of the arterial wall has been known and studied for centuries. As a physical phenomenon, radial distension of arteries is easily explained by varying the blood pressure gradient, elastic properties of arterial wall and pressure wave reflection from the periphery (Dart and Kingwell, 2001). It is fast, noninvasive and straightforward to detect radial distension of certain arteries with ultrasound, with several published methods. One simple solution is to use M-mode ultrasound or if the B-mode is preferred, it is possible to use block matching or maximum-gradient algorithms to track the radial movements of the arterial walls (Soleimani et al. 2011). The knowledge of radial distension occurs in arteries has made ultrasound tracking and diameter measurement of the artery widely used methods for evaluating arterial health (Corretti et al. 2002; Gemignani et al. 2007; Riley et al. 1992).

The axial distension of the arterial wall is a more complicated phenomenon and much harder to measure than radial distension. Because of the technical issues involved in observing the axial distension in arterial walls, it is a relatively novel phenomenon. It was first

Address correspondence to: Heikki Yli-Ollila, KYS Kuvantamiskeskus/KFI-yksikkö, PL 1777, 70211 Kuopio, Finland. E-mail: heikki.yli-ollila@kuh.fi

discovered in 1950s but was considered negligible compared to the radial distension in these blood vessels (Lawton and Greene 1956). By using modern high-resolution ultrasound imaging Cinthio et al. (2006) were able to demonstrate that the amplitude of axial distension was equal in size to the radial distension. Recently, many other groups have examined the arterial wall's axial distension (Beaussier et al. 2011; Bernal et al. 2011; Cinthio et al. 2005; Golemati et al. 2003; Soleimani et al. 2011; Svedlund and Gan 2011). The reason for the enthusiasm is the possibility that axial distension may be a new marker for pre-clinical atherosclerotic changes, such as the accumulation of the fatty streak in the intima-media layer, which changes biomechanical properties of the arterial wall.

Similar axial distension studies of the arterial wall of the common carotid artery (CCA) have been published by other research groups, but in this study all the data have been collected non-invasively, and the information obtained from the radial and axial distensions are combined to measure the overall movement of the arterial wall. In addition, a new contrast optimization technique is added to the widely used speckle-tracking algorithm (block matching) and a large variety of new possible indices of arterial stiffness are introduced. As a separation to many earlier studies, the motion tracking software is designed in such a manner that it is user friendly and compatible with a large variety of ultrasound scanners. To validate the radial and axial displacement measurements of the CCA with this method, a reproducibility analysis tool is included to the software. All the results presented in this study have been calculated with that tool.

MATERIALS AND METHODS

Radial and axial movement analysis software

The developed software for arterial wall motion analysis is designed to be used with ultrasound cine clips imaged from the CCA. Figure 1 represents a typical video layout used in the study, in which B-mode ultrasound image is placed on the top and a graphical electrocardiograph (ECG) trace is on the lower part of the video frame. The software was written using MATLAB (MathWorks, Natick, MA, USA) and is capable of reading the graphical ECG-information from the ultrasound recording and tracking of radial and axial movements of the arterial wall. The ECG trace is measured simultaneously with the ultrasound recording and can be synchronized with the arterial wall movements by R-spike detection.

Five user-defined regions of interest (ROIs) are motion tracked simultaneously. They are chosen such that the first three ROIs track the axial movement of arterial wall's innermost intima-media layer, the outermost adventitia layer and the surrounding tissue (Fig. 1). The first three ROIs are hand-selected to keep the sizes of the ROIs consistent; see Figure 1 for the approximations of the ROI sizes used in the axial movement tracking. The fourth and fifth ROIs track the radial movement of the distal and proximal arterial walls. In other words, the software can calculate the lumen diameter changes as a function of time. These ROIs for the radial movement tracking are chosen to be large to reduce tracking errors. The average ROI sizes used in the diameter tracking of the CCA are more than double sized compared with the ROI tracking the axial movement of the surrounding tissue (Fig. 1). In addition, the software is able to measure intima-media thickness (IMT) appropriately and to make automated corrections for some tracking errors and to the measured data corrupted by the non-zero angle between arterial wall and the horizontal plane.

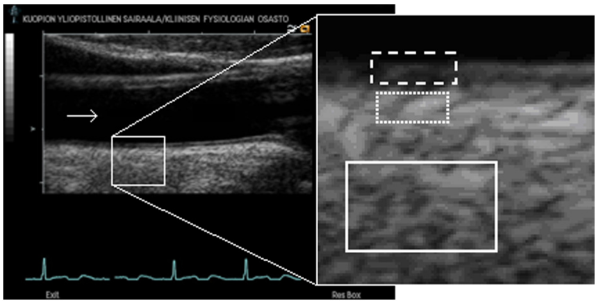

Fig. 1. The typical layout of an ultrasound video recording used in this study. The left CCA is shown in the middle of the picture. The artery was scanned in the axial direction, and the arrow indicates the direction of blood flow toward the carotid sinus (dilation in lumen area on right). The ECG trace can be seen on bottom of the picture and selected ROIs for axial motion tracking on the zoomed part of the image. ROIs are drawn with three different line types, and the average ROI sizes used in the study are in parenthetical: dashed line, intima-media ROI ($2.76 \pm 0.71 \times 0.50 \pm 0.06$ mm^2); dotted line, adventitia ROI ($3.02 \pm 0.79 \times 0.46 \pm 0.07$ mm^2); solid line, surrounding tissue ROI ($4.85 \pm 0.84 \times 1.56 \pm 0.56$ mm^2).

The basic method used in the motion tracking is 2-D cross-correlation (block matching) enhanced with luminance optimization. First, the ultrasound video is interpolated to a double size using a bi-cubic method, and ROIs are chosen by the user. After every ROI selection, the algorithm optimizes the contrast of the next full video frame by detecting the luminance of the selected ROI in the current frame and forcing the following video frame to match the luminance and dynamic range of the ROI. In this way, it is easier to find the ROI in the next frame of the video because the contrast of the image is optimized for the selected ROI; therefore, the surroundings of the ROI are intentionally over- or under-exposed. The search is conducted by 2-D cross-correlation, in which the selected ROI is matched to the next frame