Minute Roughness Measurement Using Phase Tracking for Arterial Wall Diagnosis Non-Invasively in vivo

Magnus Cinthio
Department of Electrical Measurements
Lund Institute of Technology, Lund University
Lund, Sweden
magnus.cinthio@elmat.lth.se

Hideyuki Hasegawa and Hiroshi Kanai
Department of Electronic Engineering
Graduate School of Engineering, Tohoku University
Sendai, Japan

Abstract—Early diagnosis of atherosclerosis is essential as many of the risk factors are life-style dependent. We suggest a new method to measure minute roughness of the size of micrometers of the arterial wall. The method was evaluated using three silicone phantoms sized 13 µm, 23 µm and 33 µm, respectively. The mean of the measured heights of the phantoms were 8.1 µm (SD 0.0), 23.3 µm (SD 0.2) and 29.6 µm (SD 0.1) in the forward direction, and 7.7 µm (SD 0.0), 21.9 µm (SD 0.2) and 27.3 µm (SD 3.6) in the backward direction, respectively. The phantom study shows very promising results and encourages further evaluation and in vivo investigations.

Keywords—Atherosclerosis; ruggedness; arterial wall

I. INTRODUCTION

Cardiovascular diseases constitute the major cause of morbidity and mortality in the Western World. To increase our knowledge of cardiovascular diseases, it is important to find methods, preferably non-invasive ones, to study very early manifestations of vascular disease.

Atherosclerosis is an inflammatory disease affecting the arteries [1]. The earliest changes that precede the formation of lesions of atherosclerosis take place in the endothelium. These changes include increased endothelial permeability to lipoproteins and other plasma constituents [1]. Later this is followed by a sub-endothelial accumulation of lipid-laden foam cells and associated T lymphocytes which form non-stenotic fatty streaks [1]. As the fatty streaks progress to intermediate and advanced lesions, the thickness of the arterial wall is increased, with, as we hypothesize, a following increased ruggedness.

Early diagnosis of atherosclerosis is essential as many of the risk factors are life-style dependent. Today intima-media-thickness is considered as a valuable marker of early atherosclerosis [2-6]. However, we believe by measuring the roughness of the arterial wall, atherosclerosis can be detected much earlier than possible today.

Measurement of minute roughness caused by atherosclerosis non-invasively in vivo is a challenging measurement problem. First, non-invasive in vivo examination of the common carotid artery and other superficial arteries uses ultrasound frequencies between 5–15 MHz. At these frequencies, the early roughness is magnitudes smaller than the wavelength of the RF-signal. To further complicate the measurements, the arterial wall moves both radially and longitudinally during the cardiac cycle [7-10]. Additionally, if the measurement is performed at different positions along the artery, the variations of the speed of sound introduce aberration errors.

The aim of this paper is to describe and evaluate a novel method that measures the minute roughness of several micrometers of the arterial wall using phase tracking.

II. MATERIAL & METHODS

A. The measuring algorithm

To allow measurement of roughness of the size of micrometers at one position, the recently discovered longitudinal movement of the arterial wall [10] was utilized. The lateral motion induces a change in time delay of an echo due to the surface roughness when the surface is perpendicular to the beam.

The lateral movement was measured using a recent developed in-house 2D echo-tracking method [9]. The region-of-interest was placed at an echo close to the roughness of interest. The size of the region-of-interest was approximately 0.7 x 0.7 mm in the lateral and the axial direction, respectively.

The motion in the axial direction was accurately measured using phase tracking [5] at each beam. The window used in the phase tracking estimations was approximately 0.4 mm in the axial direction.

Let \(d_1(t)\)…\(d_N(t)\) denote the measured displacement at beam 1 to N at the surface of the interested subject. To remove the global displacement, i.e., the displacement which was in common along the surface, spatial high-pass filtration was applied. The spatial high-pass filtration was conducted by first subtract the resulting displacement at one beam with the nearest beam, which resulted in the spatial differentiated displacement \(s_x(t)\).

\[
s_x(t) = \sum_{i=1}^{N} s_x(t) = d_x(t) - d_{x-1}(t) - d_x(t) - d_{x+1}(t)
\]

This study was supported by grants from the Japanese Society for the Promotion of Science (JSPS) and from the Swedish Research Council.
Thereafter each spatial differentiated displacement $s_x(t)$ was summed with its neighbor as

$$R_x(t) = s_x(t) + s_x(t) + s_x(t) + s_x(t)$$ (2)

All together this resulted in spatial filtration that gave the roughness measurement at each given beam.

### B. Collection of ultrasound information

All the investigations were performed using a modified commercial ultrasound system (Prosound II, ALOKA, Tokyo, Japan). The system was equipped with a 40-mm 10 MHz linear array transducer. The RF-data was stored in a cineloop as consecutive frames. The cineloop was transferred to a PC for post processing. The information was then imported to Matlab® (The MathWorks Inc., Natick, MA, USA), a software where the measurement algorithm was implemented.

Standard instrument settings were used but it was desirable to achieve the best possible spatial and temporal quantification. Therefore the area of interest was zoomed. Furthermore, only one transmit focus and the highest line density were chosen, resulting in a beam distance of 100 µm. These settings allowed a frame rate of 70 Hz. The sampling frequency was 40 MHz.

### C. The phantom measurements

The method was evaluated using three silicone phantoms. The silicone phantoms were produced using metallic moulds, which were manufactured using a milling machine. Saw-teeth were milled on the top of the moulds, which was designed to be 13 µm, 23 µm and 33 µm, respectively. Each mould had ten teeth and the width of one tooth was 0.5 mm.

The moulds were fixed at the bottom of a plastic cup. Thereafter a solution consisting of 95% silicone fluid (TSE3503 A, GE Toshiba, Tokyo, Japan) with 5% harder (TSE3503, GE Toshiba, Tokyo, Japan) was poured over the moulds. After that the cup was placed in a conditioner mixer (AR-100, Thinky Corporation, Tokyo, Japan) to blend substances together and to remove gases from the solution. The solution was mixed 30 plus 30 seconds.

During the ultrasonic measurements each phantom was sunk in water and attached to a step motor (ATS-930-HP, Chuo Seiku, Tokyo, Japan). The step motor was controlled by a six-axis multi-purpose stage controller (QT-CN6, Chuo Seiku, Tokyo, Japan).

To avoid measurement errors in the ultrasonic method owing to temperature dependence of the speed of sound in water, the water temperature was measured with a thermometer before and after the experiments. The water temperature was used to establish the true speed of sound [11], and thereafter this value was used to correct measurements made in the axial direction. The measurements in the lateral direction were not affected by temperature dependence of the sound speed.

Three measurements were conducted on each phantom. The phantoms were laterally moved with 2.5 mm/s in the forward and backward directions. Axially, global displacement up to hundreds of micrometers was present.

Reference measurement of the phantoms was made by a Confocal Laser Scanning Microscope (VK-9700, Keyence, Tokyo, Japan).

### III. RESULTS

Figure 1 shows an ultrasonic B-mode image of the 33 µm phantom. Figure 2 shows the resulting axial movement during the lateral movement. Figure 3 shows the roughness curve of four saw-teeth at one beam during the lateral motion for all three phantoms. Figure 4 shows the resulting ultrasonic roughness curve of the 33 µm phantom in comparison to the laser measurement.

The mean of the measured heights of the phantoms were 8.1 µm (SD 0.0), 23.3 µm (SD 0.2) and 29.6 µm (SD 0.1) in the forward direction, and 7.7 µm (SD 0.0), 21.9 µm (SD 0.2) and 27.3 µm (SD 3.6) in the backward direction, respectively. The mean widths of the saw-tooth shape were 497 µm (SD 1), 496 µm (SD 3) and 498 µm (SD 4) in the forward direction, and 512 µm (SD 3), 491 µm (SD 2) and 498 µm (SD 3) in the backward direction, respectively.
IV. DISCUSSION

Early diagnosis of atherosclerosis is fundamental as many of the risk factors are life-style dependent. Today intima-media-thickness is considered as the most valuable marker of early atherosclerosis [2-6]. However, we believe by measuring the roughness of the arterial wall, atherosclerosis can be detected much earlier than possible today.

Measurement of minute roughness caused by atherosclerosis non-invasively in vivo is a very difficult measurement problem. First, early roughness is magnitudes smaller than the wavelength of the RF-signal. To further complicate the measurements the arterial wall moves during the cardiac cycle. Additionally, if the measurement is performed at different positions along the artery, the variations of the speed of sound introduce aberration errors.

Here we have presented a new method that utilizes the recent discovered longitudinal movement of the arterial wall to measure the roughness of several micrometers of the arterial wall using very few ultrasound beams using phase tracking.

V. CONCLUSION

We have developed a novel method for non-invasive measurements of minute roughness of the arterial wall in vivo. The new method has been evaluated in a phantom study, which shows very promising results and encourage to further evaluation and to in vivo investigations.

REFERENCES

