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ARTSENS – An image-free system for noninvasive evaluation of arterial compliance

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Abstract—**Evaluation of arterial compliance is significant in cardiovascular diagnosis for early detection of coronary heart disease. We present ARTSENS, an image-free system for non-invasive evaluation of arterial compliance in-vivo. The system utilizes a single element ultrasound probe with intelligent measurement algorithms to ensure accurate evaluation of local arterial compliance without an image. The ability of the system to detect artery anatomy and measure compliance was verified by in-vivo measurements conducted on 106 subjects. The accuracy of compliance estimates were evaluated by comparison with a state of art imaging system. The measurements made using ARTSENS showed strong correlation with those made using the imaging system. The ability of ARTSENS to detect age-related trends in arterial compliance was also investigated.**

I. Introduction

Evaluation of arterial compliance is very significant in cardiovascular diagnosis for early detection of cardiac events [1]. Major clinically accepted estimates of arterial compliance are enlisted in Table I. It is evident that evaluation of the arterial compliance requires an accurate measurement of arterial distension (*ΔD*), end-diastolic diameter (D_d) and the systolic and diastolic blood pressures (P_s and P_d). Non-invasive measurement *ΔD* and D_d is typically performed with imaging systems [3],[4].

We had previously demonstrated the utility of a single element ultrasound transducer to non-invasively measure arterial distension and end-diastolic diameter [5]. The practical feasibility of an image-free modality for evaluation of arterial compliance in controlled settings has also been demonstrated [6].

Here we present ARTSENS (ARTerial Stiffness Evaluation for Noninvasive Screening), a novel system for performing automated evaluation of arterial compliance in-vivo. The system utilizes intelligent algorithms for artery anatomy detection, wall motion tracking and analysis of distension waveforms on-the-fly, to enable automated evaluation of arterial compliance with no operator inputs. The utility of this novel system in evaluating arterial compliance in-vivo was verified by measurements performed on nearly 100 subjects. The accuracy of measurements was verified by comparison with a state of art imaging system. The ability of ARTSENS to distinguish age-related trends in arterial compliance values was investigated to demonstrate the potential utility of the device in cardiovascular screening.

TABLE I. Clinically accepted measures of arterial compliance [2]

Measure of arterial compliance	Definition
Pressure strain elasticity, Ep	$\frac{D_d \times \Delta P}{\Delta D}$
Arterial Compliance, AC	$AC = \frac{\pi[D_s{}^2 - D_d{}^2]}{4\Delta P}$
Stiffness Index, β	$\beta = \frac{\ln\left({}^{P_s}/_{P_d}\right)}{\left({}^{\Delta D}/_{D_d}\right)}$

II. ARTSENS

A. System Architecture

The system architecture of ARTSENS is illustrated in fig.1. The system utilizes a single element 5 MHz ultrasound transducer (10 mm diameter, Hengxuannanshi, China) operating in the pulse-echo modality, to interrogate the carotid artery. The echoes reflected from different anatomical structures in the ultrasound path are detected by the same transducer, processed and digitized at 100 MS/s utilizing a National Instruments USB 5133 digitiser to obtain one frame of radio frequency (RF) data. Each data frame is then analyzed by the processing and measurement algorithms implemented in software. The data acquisition is repeated continuously at a frame rate of 50 frames per second. Analysis of the arterial distension over multiple frames enables the system to identify arterial walls, track wall motion and measure the arterial distension (ΔD) waveform and end-diastolic diameter (D_d). Estimates of arterial are evaluated by utilizing the measured values of ΔD and D_d along with the systolic and diastolic pressures (P_s and P_d) measured using an automated blood pressure monitor.

B. Automated measurement of arterial compliance

The major steps in the automated measurement algorithm are also illustrated in the fig.2. A detailed explanation of the various steps in the automated measurement algorithm may be found elsewhere [6],[7]. The artery detection algorithm has been validated to be capable of detecting artery locations with sensitivity more than 90 % even for SNR as low as 5 dB in the normal range of expected wall motion frequencies between 0.5 – 4 Hz [7]. The correlation based wall tracking algorithm has also been independently shown have error less than 10 % [6]. ARTSENS performs synchronized transducer excitation and data capture, and integrates wall detection and tracking algorithms along with on-the-fly distension waveform analysis to enable quick in-vivo measurements.

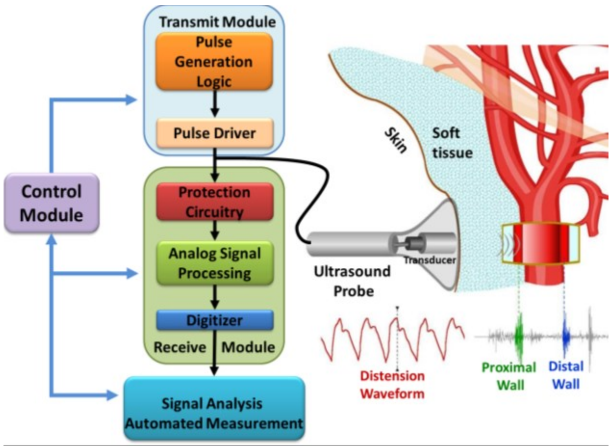


Figure 1. ARTSENS system architecture and principle of operation

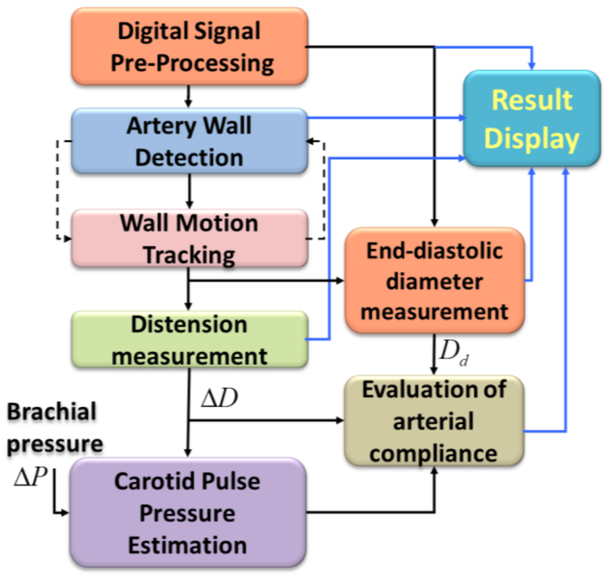


Figure 2. Signal processing and automated arterial compliance measurement

The wall detection algorithm typically identifies the artery location within 10 – 20 s, after which it passes the identified wall locations to the wall tracking algorithm. The tracking algorithm then starts continuously calculating the wall motions and generates the artery distension waveform. Simultaneously, it also checks for negative correlation between the proximal and distal wall motion waveforms evaluated every 2 s to ensure that the tracking is indeed being performed on the artery walls. The distension waveform being generated is also processed on-the-fly to identify the time-instants corresponding to the end-diastole. Every 5 successively obtained cardiac cycles are analysed to detect the time instants corresponding to the end-diastole. The corresponding radiofrequency echo signals are extracted from the data buffer and used to measure the end-diastolic diameter using a dynamic threshold based lumen diameter measurement algorithm [6]. The values of the diastolic time instants calculated in the previous step are also used to split the distension waveform into a set of 5 individual cycles from which the arterial compliance measurements are performed. Each measurement of arterial compliance is thus obtained by averaging the values obtained from 5 successive cycles.

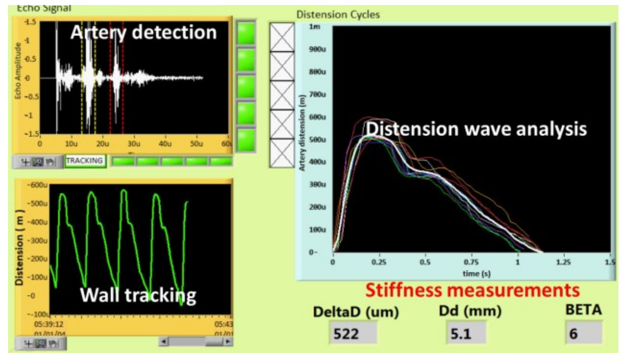


Figure 3. Graphical user interface of ARTSENS

Typically, 5 such measurements are repeated and averaged to evaluate the arterial compliance of one subject.

C. Procedure of measuring arterial compliance on-the-fly

The typical operating procedure of the device to measure arterial compliance is as follows. The location of the carotid artery is identified by palpation, and the operator places the transducer over the carotid artery. The ARTSENS device detects the arterial walls by analyzing 10 successively acquired data frames captured within 0.2 s. Once the walls are identified, it shows an indication on-screen to alert the operator to keep the transducer steady and starts wall tracking to capture the distension waveform. One measurement result is displayed as soon as 5 cardiac cycles are captured. As soon as 5 such results are obtained, the final results are available for review, and the measurement cycle stops. All the data collected in the test, along with the compliance estimates are also recorded into a database for future reference. The graphical user interface (GUI) of the ARTSENS device is illustrated in fig.3.

III. Validation of In-Vivo Measurement Performance

The performance of the wall-detection, tracking and automated measurement algorithms have already been extensively characterized by simulation studies, and experiments conducted using artery phantoms [6],[7]. To evaluate the practical feasibility of performing image-free evaluation of arterial compliance in-vivo, the prototype ARTSENS device was utilized to perform measurements on more than 100 healthy volunteers.

A. In-vivo study protocol

The objective of the study was to verify the ability of ARTSENS to measure arterial compliance in-vivo. The technical functionality of ARTSENS was validated by comparing arterial compliance indices measured using ARTSENS with those measured using a state of art imaging system (Aloka Pro α10 eTracking system).

Subject selection criteria: Both male and female subjects within the age group of 20 – 40 years were included in the study. Subjects with previous history of cardiovascular or peripheral vascular disease are not included in the study. Subjects taking cardiovascular medication or any other anti-hypertensive medication were also excluded from the study.

Data Collection: 106 healthy subjects with no history of cardiovascular or peripheral vascular disease were included in the study. Each subject's name, gender, contact details, medical history, height, weight and BMI, data were collected and stored in database. An informed consent form duly filled and signed by subjects was obtained.

Measurement protocol: The subject was seated comfortably with back support and allowed to relax for 5 minutes. The brachial blood pressure was measured using an automated blood pressure monitor (Omron HEM-7101) and entered into ARTSENS and the Aloka imaging system.

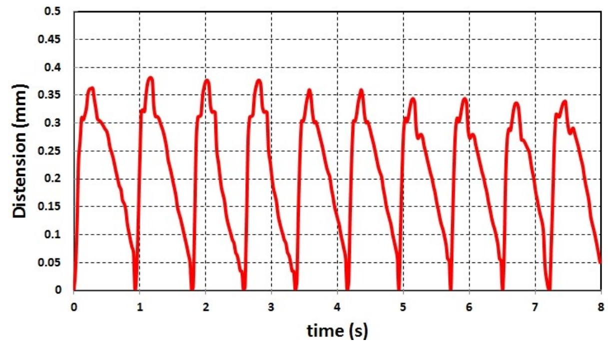
(a) ARTSENS measurement: The carotid artery location was identified by palpation and the transducer was positioned over the artery. The transducer was angulated till the system indicated that the artery walls were identified and then the transducer was held steady while wall tracking was performed and arterial compliance estimates were given by the device.

(b) Imaging system measurement: The carotid vessel was imaged using a 10 MHz linear array probe. The proximal and distal walls of the artery were manually identified on the B-mode image and then the wall motions were tracked by the system. The tracking gates were positioned towards the carotid artery lumen, next to tunica intima layer. When a steady waveform was obtained for 4-5 cycles, imaging was frozen to acquire the data which were accumulated over the period to start arterial stiffness analysis. A few successively acquired cycles of the diameter waveform that had stable wave shape were selected (as per guidelines given in the machine operation manual) to perform evaluation of arterial stiffness.

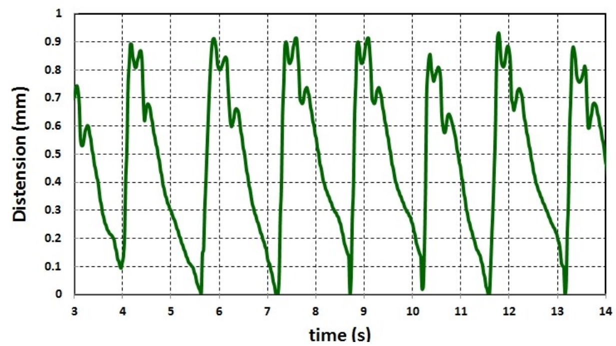
B. Results from in-vivo study

Of the 106 subjects enrolled in the study, measurements could not be made on 3 subjects, as neither ARTSENS nor Aloka eTracking could provide stable distension waveforms More than 10 stable arterial distension waveform cycles could be easily obtained from the remaining 103 subjects. Typical arterial distension waveforms measured from a few subjects are illustrated in fig. 4. It can be seen that ARTSENS can easily capture more than 10 consecutive cycles of arterial distension waveform with good consistency in wave shape. The observation of a clear dicrotic notch in the measured waveforms also indicates that the system has enough bandwidth to capture the hemodynamic features of the distension waveform as well.

In 19 subjects the arterial distension measured by ARTSENS was found to be differ from that measured by the Aloka system by more than 0.2 mm. As typical carotid distensions are in the range of 0.5 – 1 mm, these subjects were treated as outliers due to errors in the measurement protocol, and eliminated from further data analysis. A comparison of arterial distension measured by ARTSENS with that measured using Aloka system is shown in fig. 5. The correlation coefficient between distension measured by ARTSENS and that measured by the Aloka imaging system was 0.8. A similar comparison for end-diastolic diameter demonstrated a correlation coefficient of 0.64. It is evident that measurements made by ARTSENS clearly correlate with those made by the Aloka imaging system.



(a)



(b)

Figure 4. Typical distension waveforms measured on two volunteers

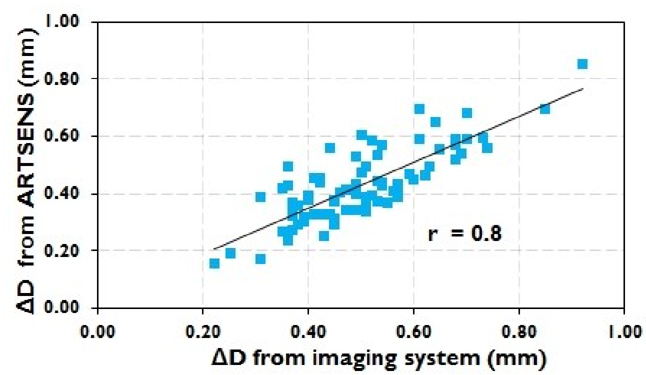


Figure 5. Comparison of arterial distension measured in-vivo by ARTSENS and Aloka eTracking system, on 84 subjects.

A comparison of the arterial compliance indices measured by ARTSENS with those made by Aloka eTracking system is illustrated in fig.6, fig.7 and fig.8. The tight grouping of the data illustrated in these figures indicate that there is a positive and statistically significant relationship between arterial compliance indices measured by ARTSENS and Aloka eTracking system. It was found that the stiffness index, β, measured by ARTSENS showed a correlation coefficient of nearly 0.71 with that measured using Aloka eTracking. Similar strong correlations were observed in other indices of arterial compliance as well, with the pressure strain elasticity, *Ep* demonstrating a correlation coefficient of 0.74 and the arterial compliance, AC showing a correlation coefficient of 0.71.

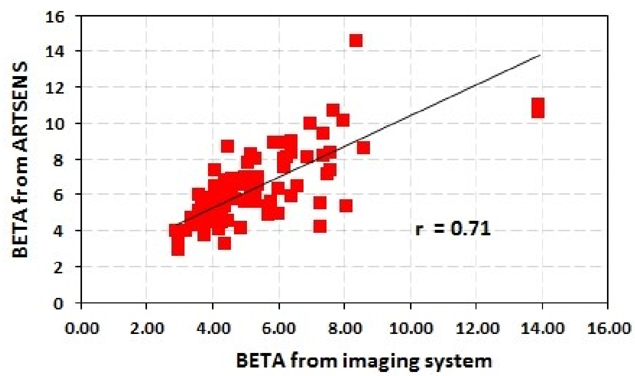


Figure 6. Comparison of stiffness index,β

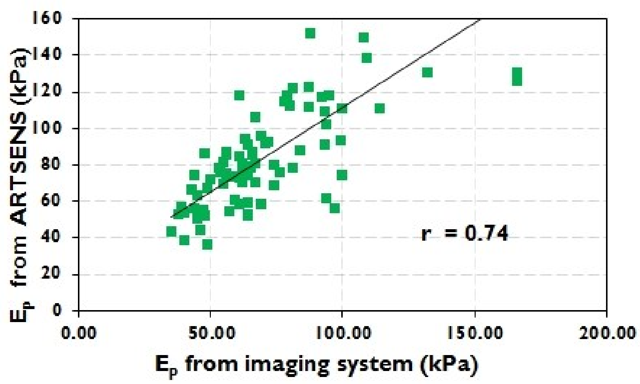


Figure 7. Comparison of pressure strain elasticity, *Ep*

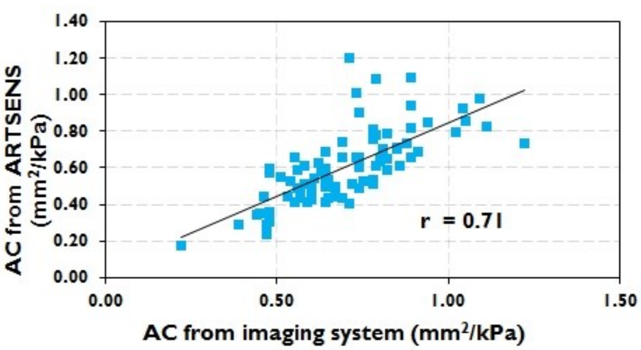


Figure 8. Comparison of arterial compliance, AC

C. Age-related trends in arterial stiffness

To investigate the ability of ARTSENS to detect age-related changes in arterial compliance, the data measured in the in-vivo study was re-examined. It can be seen from fig.9 that the arterial stiffness index, β increases with age. The increase in arterial stiffness with age was also evident in the pressure strain elasticity, E_p. The arterial compliance (AC) was found to decrease with increased age as shown in fig.10. This illustrates the ability of ARTSENS to detect the changes in arterial stiffness that occurs due to aging, thereby indicating potential application in cardiovascular screening and evaluation of vascular age.

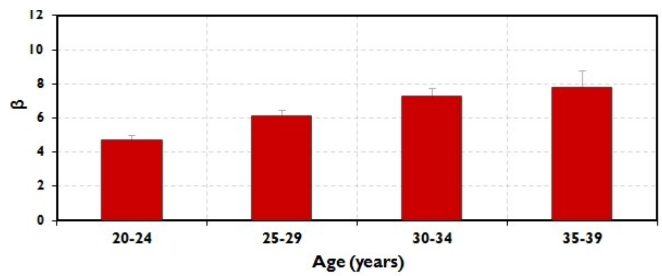


Figure 9. Age related increase in arterial stiffness index,β, observed in measurements made using ARTSENS

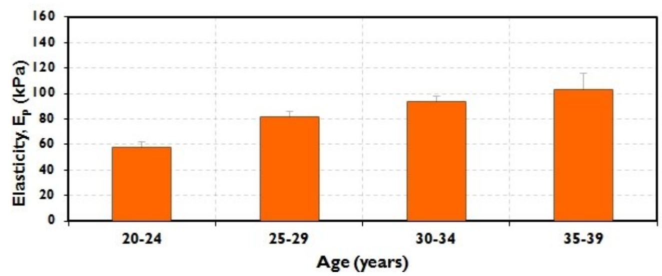


Figure 10. Increase in arterial elasticity,Ep, with age, observed in measurements made using ARTSENS. Error bars indicate standard error

IV. Conclusion

An image-free system for non-invasive, automated evaluation of arterial compliance in-vivo was presented. The ability of the ARTSENS system to evaluate arterial compliance was verified by in-vivo measurements performed on 106 subjects. The arterial compliance indices measured by the ARTSENS system demonstrated strong correlation with the values obtained using a state of art imaging system. The ARTSENS device was demonstrated to have enough sensitivity to detect age-related trends in arterial compliance parameters, thereby highlighting the possibility of potential use in large scale cardiovascular screening studies.

V. References

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