Ultrasound Signal Quality Parameterization for Image-free Evaluation of Arterial Stiffness

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***Abstract*— We are in process of developing an image-free, single element ultrasound system for automated evaluation of arterial stiffness, we call it ARTSENS. The lack of a guiding image for arterial visualization necessitates intelligent analysis of ultrasound radio frequency (RF) echo signals to obtain reliable measurements. In this paper, we propose a novel algorithm to parameterize the echo signal received from the common carotid artery (CCA) to improve accuracy and reliability of arterial stiffness measurement. The echo signal quality is parameterized using features such as sharpness of arterial wall and energy ratio. A signal quality score is calculated by integrating the results from each feature. This score is used to triage the set of available echo signals recorded from each subject and select the best signal for computation of stiffness values. The performance of signal quality algorithm is tested using a database of carotid artery echo signals recorded from 28 human volunteers. It was observed that both the accuracy and reliability of the stiffness measurements were improved after triaging using the signal quality parameterization algorithm.**

I. INTRODUCTION: NEED FOR SIGNAL QUALITY PARAMETERIZATION

Elasticity of arterial walls is an indicator of vascular health and increased arterial stiffness is an early sign of vascular damage. In view of the high incidence of cardiovascular diseases (CVD) a low cost, mass screening instrument for CVD is desirable, especially in developing nations [1-2].We have developed a system called ARTSENS® (ARTerial Stiffness Evaluation for Noninvasive Screening) that provides a reliable estimate of arterial stiffness for use in vascular screening. It is an automated, image-free system that may be operated by a general medical practitioner with no sonography expertise.

We had previously demonstrated and validated the image-free ARTSENS ultrasound system for evaluation of arterial compliance [3-4]. The principle of automated carotid artery stiffness evaluation using ARTSENS is shown in Fig. 1. A 5 MHz, single element ultrasound transducer detects echo signals (called frames) from the artery at the rate of 50 frames/second. The acquired frames are sampled and digitized at 100 MSPS and passed through automatic wall identification and tracking algorithms [6]. A sliding window covariance (SWC) based technique is used to detect artery walls. The motion of these detected walls are tracked using cross correlation based method to give distension cycles to measure lumen diameter and to calculate stiffness parameters [7].

The accuracy of the artery detection and measurement algorithms are influenced by the morphological features of the echo signals obtained from the artery walls. For accurate measurements, clear representation of arterial wall structure in ultrasound echo signal is necessary, especially in the tracking phase. While the measurement is being performed using the hand held ultrasound probe, slight movement of the probe can cause the beam to be directed away from the diameter of the artery, resulting in both reduced strength of the artery echo signal and wider pulse width of received echoes as the artery moves out of focus of the beam. This pulse spreading will cause underestimation of artery lumen diameter and stiffness. In such a situation, immediate feedback should be provided to the user, to adjust position of probe. Further, the measurement algorithm has to confirm that final results are unaffected by the relatively poor quality wall echoes that were recorded for a while during the measurement process. While this may be attained by continuously running the SWC based wall detection algorithm during the tracking phase as well, the computation intensity of the detection algorithm will limit the overall frame rate and affect real time usability of the device. Hence an intelligent, yet computationally efficient method needs to be developed to quantify the signal quality for providing real time feedback and improving reliability of final results by performing stiffness measurements only under good signal quality conditions.

In this paper, we present an algorithm to quantitatively estimate the clarity of artery walls within the detected echo signal. The signal quality is evaluated by considering the sharpness of the arterial wall echoes as an important indicator of accurate probe positioning for correct representation of arterial walls within the echo signal. In this proposed method energy ratio and sharpness of walls are taken as parameters to specify signal quality. Subsequently, a quality score is computed that can be used to triage good signals for performing stiffness measurements. Algorithm blocks explained in this paper are highlighted with yellow colour (dotted line) in Fig. 1. Improvement in accuracy and reliability of stiffness measurements, subsequent to triaging using the signal quality estimate, is demonstrated on a data set collected by in-vivo measurements on 28 volunteers.

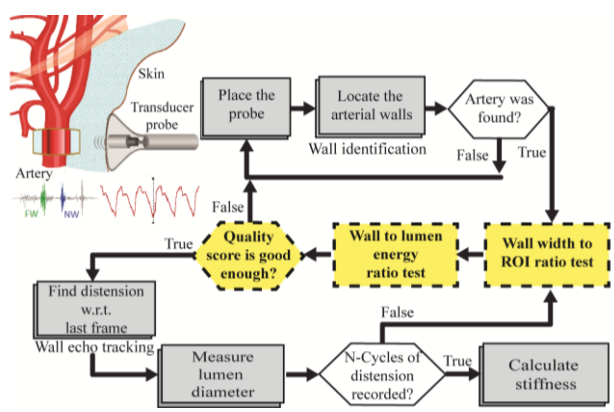

Fig.1 State diagram of ARTSENS system algorithm.

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II. SIGNAL QUALITY TEST ALGORITHM

An "ideal" echo frame of a subject's artery may be visualised as indicated in Fig. 2a. This frame contains (a) two arterial walls, and (b) the arterial well in between walls. The high amplitude of the artery wall echoes, and their narrow pulse width indicated by the sharpness of the echoes clearly distinct both the artery walls and the artery well in between the walls, from the background signals and other echoes. To ensure good measurement both walls should be distinctly identifiable. A representative good quality ultrasound echo frame, in which the arterial wall echoes are distinctly identifiable is shown in Fig. 2b. In such cases, ARTSENS gives reliable measurements from the echo frame. A discussion of the important features that may be used to characterise the quality of the signal is given below.

A. Amplitude ratio

The quality of the signal may be estimated by measuring the ratio of the maximum amplitude of both walls to the amplitude of the well. This ratio should be greater than a specified threshold for good quality signals.

The amplitude ratio is defined as the ratio of maximum amplitude in near walls (NW) or far wall (FW) ($maxA_{NW}$ or $maxA_{FW}$) to maximum amplitude in well ($maxA_{well}$). The ratio given as in (1a and 1b). The location of the NW and FW are provided by the wall motion tracking algorithm [6].

$$A1 = maxA_{nw} / maxA_{Well} \qquad (1a)$$

$$A2 = maxA_{fw} / maxA_{Well} \qquad (1b)$$

The fluctuations of the amplitude as well as the location of the walls within each cardiac cycle affects the values of A1 and A2 and hence this is not a very reliable measure for practical use. A more reliable method is developed using more parameters as described in the following sections. We compute the amplitude ratio only to compare with other proposed parameters.

B. Width of wall / Sharpness of the wall echoes

Good quality artery wall echoes are characterised by narrow pulse width, apparent in the sharpness of the artery wall echoes visualised in the signal. The sharpness of the wall is found based on energy envelope technique. We calculate moving point energy envelope (M) with window length of W for each N-point data frame (F) as defined in (2).

$$M(n) = \frac{\left\{\sum_{k=n-\left[\frac{W}{2}\right]}^{k=n+\left[\frac{W}{2}\right]} F(k)^2\right\}}{W}, \text{for } \left[\frac{W}{2}\right] < n < N - \left[\frac{W}{2}\right] \qquad (2a)$$

$$= 0, \text{for all other } \; n < N$$

$$M = \{M(1), M(2), \ldots M(N)\} \qquad (2b)$$

Regions of interest (ROI) corresponding to artery wall locations are extracted from the M signal to extract the energy envelope of both walls and the artery well. A threshold level of 10% of maximum peak was applied to determine wall width, as the point where envelop touches threshold value for 1st time when coming down from peak location. ROI and wall widths are calculated as represented in Fig. 3. Sharpness of the wall is calculated as ratio of ROI & wall width. For both walls wall width ratio is calculated as (3a, 3b).

$$W1 = ROI/width\_NW \qquad (3a)$$

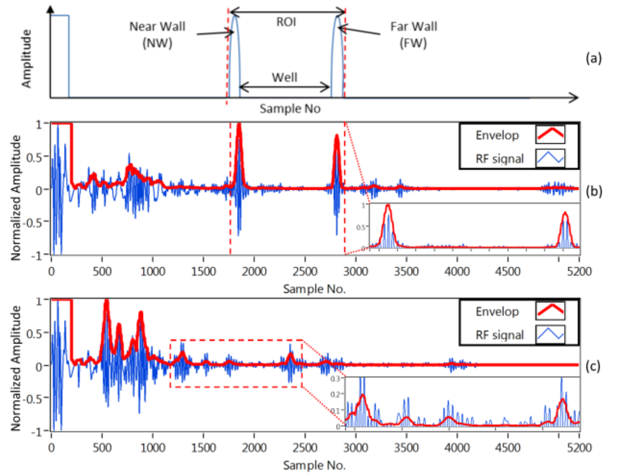

Fig. 2 (a) Ideal signal frame envelope, (b) subject's good quality ultrasound echo frame (normalized by maximum amplitude), (c) low quality echo frame, wall structure (ROI) in echo frame marked by dashed line and shown in inset.

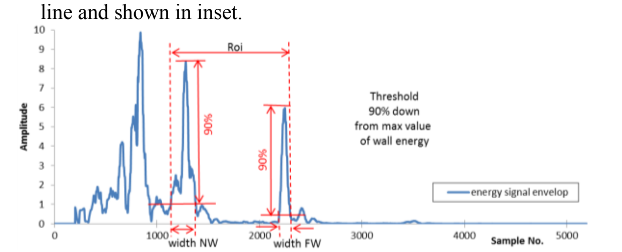

Fig. 3 Wall width measurement by energy envelope method.

$$W2 = ROI/width\_FW \qquad (3b)$$

C. Energy ratio of wall

The width of wall is found out for first frame using wall width estimation based on energy envelop of RF signal. This same wall width is moved in subsequent frames according to the wall motion measures given by tracking algorithm. Energy of wall (E_{nw}, E_{fw}) and well (E_{well}) is found out by (4).

$$E = \frac{1}{n-m}\sum_{k=m}^{k=n} F(k)^2 \qquad (4)$$

Where m= start indices & n=end indices of wall or well Energy ratio is taken as wall energy/ well energy for both walls, so we will get 2 ratios as in (5). These ratios are calculated for each frame.

$$E1 = 20 \, Log\,(E_{nw}/E_{well}) \qquad (5a)$$

$$E2 = 20 \, Log\,(E_{fw}/E_{well}) \qquad (5b)$$

D. Estimating expected range of variation of signal ratios

To evaluate the expected range of variation of each of the above mentioned signal ratios, an in-house data base ultrasound echo signals previously recorded from 21 subjects with ARTSENS was used. The energy ratios E1, E2, width ratios W1, W2, and maximum amplitude ratios A1, A2 were measured for every frame and compared along with arterial distension waveform. A distension waveform recorded for one full cardiac cycle is denoted as distension cycle. The variation of these ratios within each distension cycle was noted. Cycles with good quality echoes at NW and FW, characterised visually, were manually selected. A total of 175 cycles with good NW and 220 cycles with good FW were selected. Total 338 cycles with low quality RF frame were

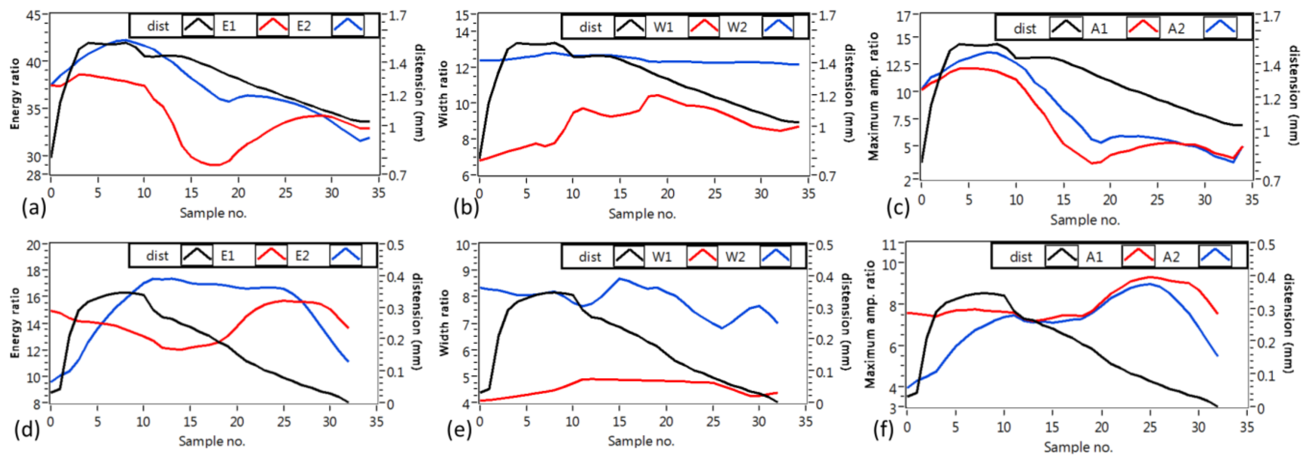

Fig. 4 Variation of various parameters over one distension cycle in good quality signal and low quality signal, (a)(b)(c) Variation in ratios E1(NW) , E2(FW) , W1, W2, A1, A2 for good quality signal, (d)(e)(f) variation in same ratios for low quality signal.

also detected. As the signal ratios were fluctuating within each cardiac cycle, the minimum and maximum value of ratios in each selected cardiac cycle were compared to get overview of expected values in each ratios.

Further, subject-to-subject variations were also observed in the minimum and maximum values. Since all these cycles are of known quality this exercise gives the expected range for each parameter. These values also help in quantifying weightage for each parameter. Fig. 5 gives average and standard deviation in min and max value for each ratios.

E. Calculation of signal quality scores.

To determine quality of the signal a scoring pattern is defined. A scale of 0 to 100 is selected where score 100 corresponds to best quality of signal. Quality estimate for both walls are determined separately.

As can be seen in Fig. 5 that in good quality signal NW energy ratio is around 30. In FW it is near 28. Similarly wall width ratio in good quality signal in NW was around 8 and for FW it was 10. From this numbers we developed the following scheme to allocate scores to both walls.

$$A = (E1 - 10) \times 2 \tag{6a}$$

$$B = W1 \times 2 \tag{6b}$$

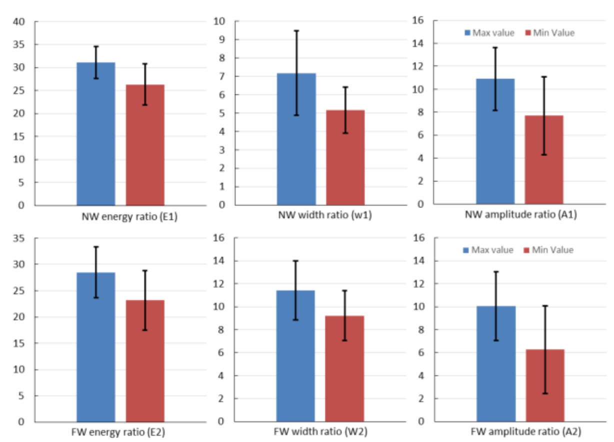

Fig. 5 Minimum and maximum values of all ratios are taken for each cycle. Averaged these values for all selected cycles. Standard deviation is shown as error bar. Shows variation between maximum and minimum for amplitude ratio in NW as well as in FW is large so cannot be used for signal quality score.

$$Q_{nw} = A + B \tag{6}$$

$$C = (E2 - 8) \times 2 \tag{7a}$$

$$D = W2 \times 2 \tag{7b}$$

$$Q_{fw} = C + D \tag{7}$$

$$SQ = Q_{nw} + Q_{fw} \tag{8}$$

The maximum values of A and C were limited to 40 while those for B and D were limited to 20.

From equation (6, 7) we calculate NW and FW quality scores (Q_{nw} and Q_{fw}) for each subject data. Average of all this scores comes about 50 for each wall. All values for good quality signal ranges above 35, so it is safe to assume that signal quality score above 35 as good quality signal. NW & FW quality scores are added (8) to give signal quality estimate for signal frame.

III. Verification of Algorithm

The signal quality parameterisation algorithm was implemented in a LabVIEW virtual instrument. Ultrasound echo frames and approximate location of walls were given as input. Signal quality scores were calculated using proposed method. The signal quality score was used to triage and select good cycles. Artery stiffness measurements were performed on these selected cycles. These measurements were then compared with (a) measurements performed using ARTSENS on all cycles without any triaging, and (b) measurements performed using a reference ultrasound imaging system (Aloka Prosound α10 with eTracking). An in-house database of ultrasound echo signals recorded from 28 healthy human volunteers was used to verify algorithm. For all subjects, distension cycles were recorded along with quality score(SQ).

Variations in measured end-diastolic diameter D_d, attributed to low signal quality significantly affects reliability of stiffness measures. The signal quality algorithm was used to reduce this variation, by selecting good quality cycles based on quality score given by algorithm for each subject. In 24 subjects, it was observed that the standard deviation (SD) of D_d was reduced after triaging good quality cycles as shown in Fig. 6. This demonstrates that repeatability of measurement increases when only good quality echoes are used while computing D_d.

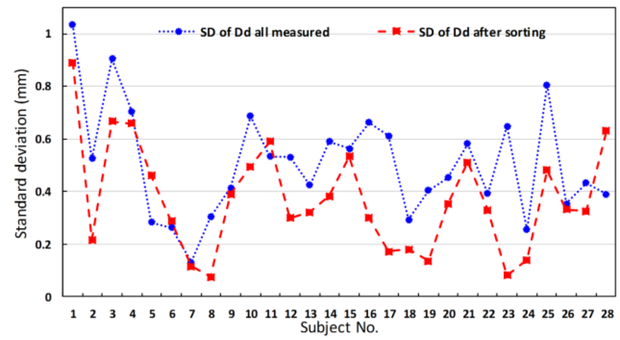

Fig. 6 Plot of SD of D_d values before and after sorting by signal quality score. After sorting by quality score, SD reduced for 24 subjects out of total 28 subjects data.

Local arterial stiffness is computed using D_d and arterial distension (ΔD) along with blood pressure values [5]. Systolic and diastolic pressure (P_s and P_d) are used to calculate Stiffness index (β) and Elastic modulus (Ep), as given by (9) and (10). Where ΔP is change in blood pressure (i.e. P_s - P_d).

$$\beta = \frac{\ln (P_s/P_d)}{\Delta D/D_d} \tag{9}$$

$$Ep = \frac{\Delta P \times D_d}{\Delta D} \tag{10}$$

β and Ep measured from state-of-the-art image based system is compared with calculated β and Ep value (Fig. 7). β calculated by instrument without triaging by quality score has correlation of 0.81 with image based measurement. Correlation coefficient improved to 0.87 when cycles are selected based upon proposed signal quality algorithm. Similarly correlation in Ep measurement (Fig. 8) is improved from 0.83 to 0.91. Improvement in accuracy of ARTSENS measurement is also apparent from Bland Altman plot in Fig. 7. The mean error for β is reduced from 0.302 to 0.0782 and that for Ep from 3.57 to 1.43, after triaging based on signal

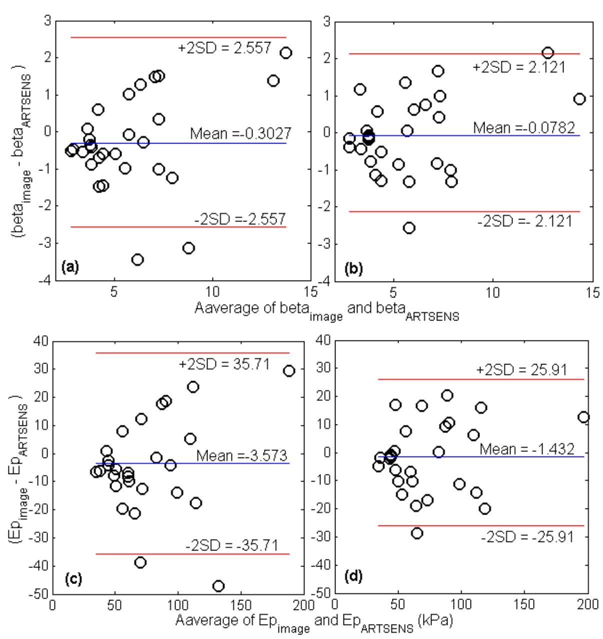

Fig. 7 Bland Altman plot for β and Ep values, compression between values measured by imaging system and calculated by ARTSENS system, (a, c) before and (b, d) after sorting with signal quality score. Mean and SD of error reduced after triaging with signal quality score, establishing improvement in measurement accuracy and reliability.

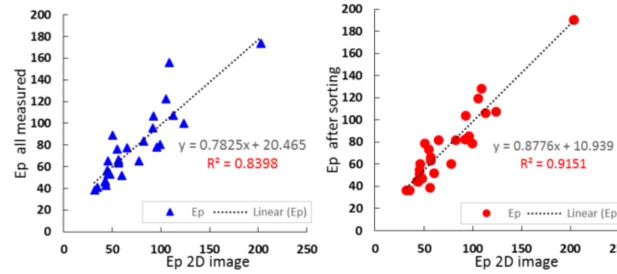

Fig. 8 Correlation between Ep values measured by imaging system and calculated by ARTSENS system, (a) before and (b) after sorting with signal quality score.

quality score. The standard deviation of errors was also reduced subsequent to triaging, indicating an improvement in measurement reliability.

Signal quality score can also be displayed to user in order to give feedback about quality of echo. This simple feedback from instrument gives user overall indication of strength of the artery echo signal. Even inexperienced person can be trained easily to record data in maximum possible signal quality.

IV. Conclusion

An algorithm to parameterize the quality of RF echo signal used in image free evaluation of arterial stiffness was presented. The signal quality score was computed using sharpness of arterial wall and energy ratio. It enables automatic selection of good echo signals to improve accuracy and reliability of stiffness measurement. The algorithm also helps operator to obtain best quality measurements without deep understanding of ultrasound echo signal and wall characteristics. The operator can be easily trained to correctly position ultrasound probe using the quality score as a feedback indicator. The algorithm is independent of maximum amplitude of wall echoes. This algorithm improved the performance and reliability of measurement in ARTSENS, an image-free ultrasound system for arterial stiffness measurement.

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