An Improved Method for Detection of Carotid Walls in ARTSENS

Ashish Kumar Sahani[1], Malay Shah[1], Jayaraj Joseph[2], Mohanasankar Sivaprakasam[1, 2]
[1]Department of Electrical Engineering, Indian Institute of Technology Madras, India
[2]Healthcare Technology Innovation Centre, Indian Institute of Technology Madras, India
ee10d043@smail.iitm.ac.in

Abstract— **We have been developing a fully automated ultrasound based imageless system to facilitate mass screening of patients for future risk of cardiovascular diseases. The device shall enable a general medical practitioner to non-invasively measure the local arterial stiffness of common carotid artery (CCA) and has been acronymed ARTerial Stiffness Evaluation for Non-invasive Screening (ARTSENS™). Complete automation of the system requires providing assistance in placement of probe over the CCA location and automatic identification of approximate location of proximal wall (PW) and distal wall (DW) of the CCA. In this paper we propose a method based on temporal motion of PW and DW over successive A-Mode frames to locate the CCA. We evaluated the performance of the algorithm with data obtained from CCA of 30 subjects. It could correctly identify the CCA in more than 70 % of trials. We also propose a method for pre-processing the frames by using the transmitted pulse wavelet. This improved the detection rate significantly. False positives were always less than 6% of total detections.**

I. INTRODUCTION

Over past few years we have been developing a low-cost system for facilitating screening of large population for cardiovascular diseases, ARTSENS® [1]. ARTSENS uses a single element ultrasound transducer to measure the stiffness of CCA. It is a fully automatic imageless system thus, can be used by a general medical practitioner with no knowledge of ultrasound modality.

Placement of the probe at correct anatomical location is of utmost importance in any ultrasound device. In conventional B-Mode imaging systems for measurement of arterial stiffness, probe is placed on CCA by a trained radiologist by looking at the arterial anatomy on B-Mode image display. After the placement of the probe the arterial walls are generally identified by the operator with software cursors. In some cases this may be done semi-automatically [2] [3] or automatically [4]. Once the PW and DW locations are identified they are tracked over frames to obtain the distension waveform which is subsequently used to calculate arterial stiffness [5]. ARTSENS is designed for usage by an operator, untrained in ultrasound thus, has to be fully automatic in all its operations. It is a low cost imageless system which acquires only A-Mode ultrasound frames. There are two major challenges in automation of this system.

a) Enabling an untrained general practitioner to place the probe at the correct anatomical site with right orientation, in absence of an image feedback.
b) Automatic identification of approximate locations of PW and DW for initiating wall tracking.

We had earlier reported a method for automatic detection of CCA based on the characteristic out of phase motion of PW and DW [6] which effectively used only two successive frames for identification of CCA and had a relatively high false positive rate.

In this paper we explain an improved method of automatically locating the CCA using negatively correlated motion of the walls analyzed over multiple successive frames. This method more uses the information from multiple frames more effectively with lesser computational load. We also propose a method for pre-filtering the frames by using the transmitted pulse wavelet. We validate the performance of the algorithm by measuring its detection rate on datasets obtained from 30 human volunteers. The algorithm could locate the CCA correctly in more than 70 % of the cases. It has a very low false positive rate and we could successfully reject frames without the CCA. The pulse wavelet based pre-processing boosts the detection rate by more than 6 %.

II. THE ARTSENS HARDWARE

The ARTSENS hardware board is custom made for driving the single element ultrasound transducer which has a center frequency of 5 MHz. An onboard microcontroller generates a single high voltage pulse with pulse duration of 100 ns and a pulse repetition frequency of 50 Hz (f_{PRF}). The received echoes are digitized at a sampling rate of 100 MSPS, using a high speed digitizer (NI USB – 5133), for about 52 µs after firing each pulse. Assuming the speed of sound as 1540 m/s in tissue we have a range of vision of 40 mm and 130 sample points per mm (M). Details of hardware implementation were reported in our past publication [1].

III. ARTSENS SOFTWARE BLOCKS

To identify the CCA, we search for two prominent echoes that are present next to each other and are moving in opposite phase. In case, such echoes are not present we reject the frames as not having the CCA. The CCA walls are detected in real-time while the operator moves the probe over the neck of the patient. The user is indicated about the detection of CCA as soon as the probe is on the artery. Operator is required to steadily hold the probe after this indication, but the probe may be in motion and user may overshoot the artery position. We confirm the correct placement by running the wall detection algorithm on few more frames. After the algorithm confirms the correct position of the probe, we track the echoes from PW and DW

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

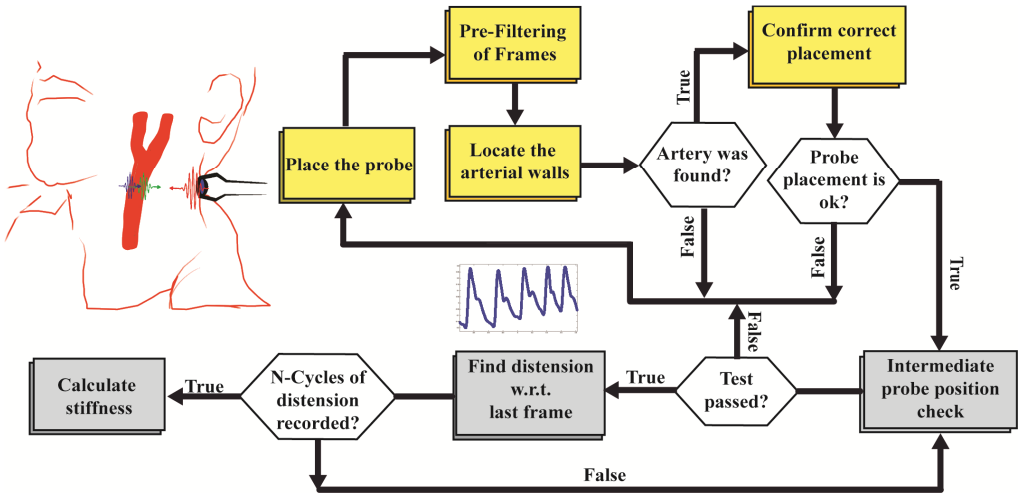

Fig. 1. The state diagram of ARTSENS processing algorithm is shown. Placement of the single element probe on neck of the patient is illustrated. Explanation of the block diagram can be found in Section III.

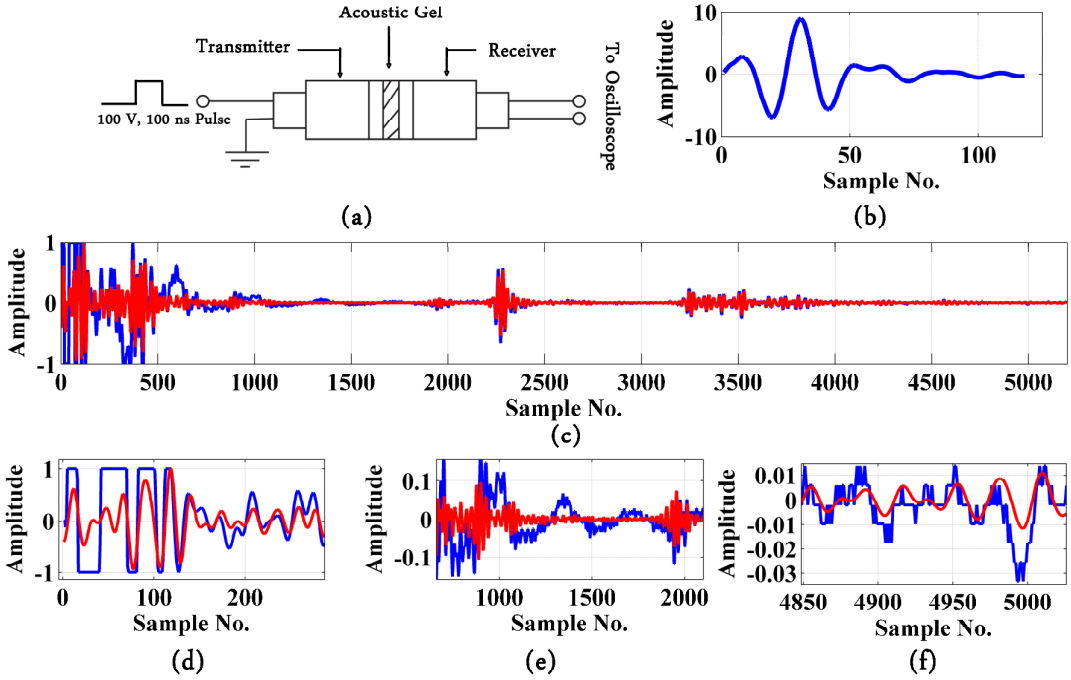

Fig. 2. (a) We placed another receiving transducer on the face of the transmitter and obtained the exact transmitted pulse. (b) The transmitted pulse wavelet is recorded at the terminals of the receiving transducer (c) The raw data frame (blue) and the frame filtered with the pulse wavelet (red) are plotted over one another. Zooming into particular regions of frame shows that (d) filtering suppresses the initial saturation region and (e) suppresses ringing due to impedance mismatch between transducer and pulse driver circuit. (f) Speckle and quantization noise were reduced.

temporally to plot the distension curve. During the tracking the operator is required to hold the probe in the same position over several seconds. There is a chance that probe may move out of position due to operator hand motion or patient body movement. We need to check the correctness of probe position and keep a pulse on signal quality while tracking the walls. This check is done by set of methods based on measurement of ratio of energy of wall echoes to lumen echoes and analysis of sharpness of echoes [7]. If this intermediate check fails then we indicate the user to reposition the probe. Once we obtain distension curve over required no. of cardiac cycles we find the diastolic lumen diameter [8], calculate the stiffness and stop the measurement. The entire state diagram for the algorithm is illustrated Fig.1. In this paper we only explain the algorithm for detection of CCA which are employed in software blocks highlighted in yellow in fig. 1.

IV. Pre-Processing of ARTSENS Frames

ARTSENS acquires A-Mode frames from a single element ultrasound probe. A typical raw data frame (R) obtained from CCA of a subject is shown in fig. 2(c). We use a novel method of filtering the frames that suppresses transducer saturation, speckle and quantization noise and ringing due to impedance mismatch between transducer and pulse driver circuit. First of all we extracted the exact pulse being emitted by the transducer by placing another identical transducer on the face of the emitting transducer (fig. 2(a)). We digitized the induced voltage across the terminals of the receiving

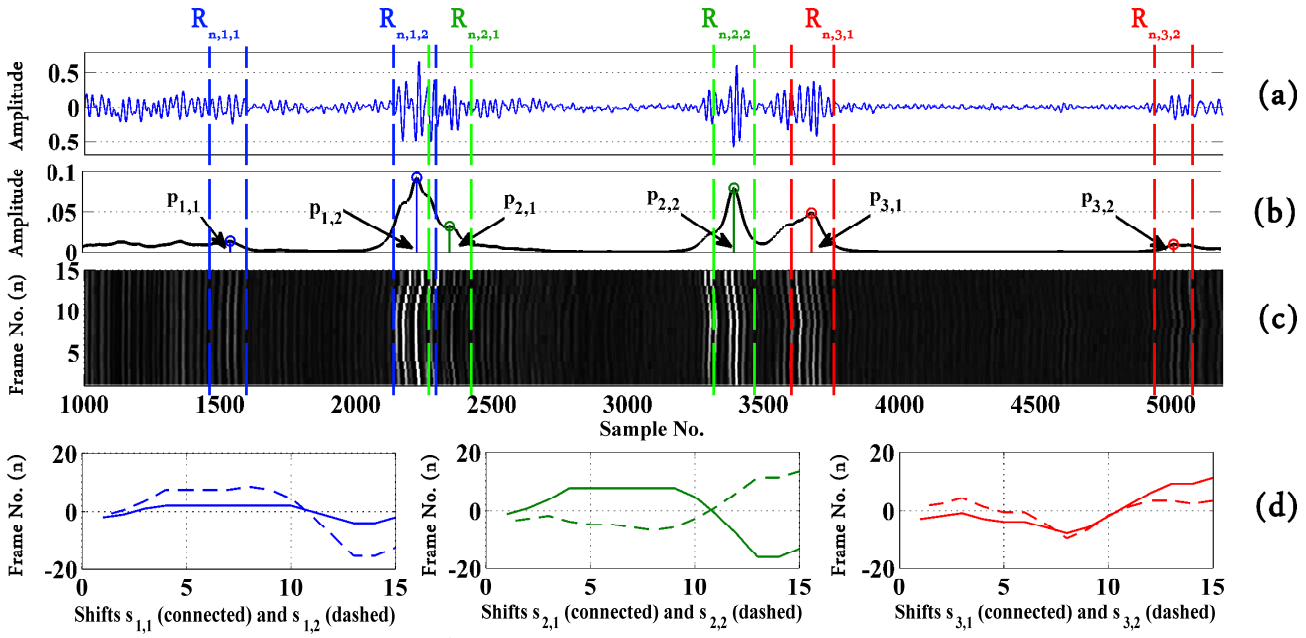

Fig. 3. (a) Shows the region of pre-processed frame (f_k), where we have significant echoes. (b) Shows the short time energy (e) for the frame shown in fig. 3(a). The detected peak pairs are marked and grouped by different colors. (c) The F array is shown. The motion of the echoes from the tissues can be clearly visualized. Figs 3(a), 3(b) and 3(c) share the common horizontal axis. The ROIs chosen around peak locations are marked by vertical cursors. (d) The shift array pair for each of the three ROI pairs are plotted in three separate figures. Clearly only $s_{2,1}$and $s_{2,2}$are negatively correlated while all others are positively correlated. Thus $p_{2,1}$and $p_{2,2}$correspond to PW and DW respectively.

transducer and recorded the exact pulse (p) as shown in fig. 2(b). We find the correlation (C) of p with the received raw data frame (R). This enhances the regions where there are replicas of the pulse that originate out of reflections from echogenic tissues. Let R be the raw frame with N points. We zero-pad the pulse p, so that it has N points and find the correlation C given by (1a). The filtered frame f is given by (1b). Fig. 2(c) show the filtered frame plotted over the raw data frame. Fig. 2(d), fig, 2(e) and 2(f) show the effect of filtering on different artifacts of the signal.

$$C(j) = Corr(R,p)_j = \sum_{k=1}^{N-1} R_{k+j} \times p_k \qquad (1a)$$

$$-N+1 \le j \le N-1$$

$$f = \{C(0), C(1), \dots, C(N-1)\} \qquad (1b)$$

V. Detection of CCA in Frames

Let k^{th} frame having N points be denoted by f_k. We push the frame into a first-in first-out (FIFO) matrix F, which stores last U frames as its rows (2) (fig. 3(c)).

$$\mathrm{F}_k = \begin{Bmatrix} f_{k-U+1} \\ f_{k-U+2} \\ \cdot \\ \cdot \\ \cdot \\ f_k \end{Bmatrix} \qquad (2)$$

We find the short time energy (e) of the current frame (f_k) given by (3) (fig. 3(b)).

$$e(n) = \sum_{p=n-\frac{M}{2}}^{p=n+\frac{M}{2}} \{f_k(p)\}^2, where, \frac{M}{2} < n < N + \frac{M}{2} \qquad (3)$$

There may be multiple prominent echoes from various tissues on the path of the ultrasound beam. There are only two pulsating structures in the neck, the CCA and the jugular vein. Jugular venous pulse is generally not visible in sitting position for patients with normal JVP; if otherwise, it can be suppressed by mild pressure of probe. The pulsation of the CCA can push against the neighboring tissues and induce them to motion. As can be seen in the M-Mode image in fig. 3(c) PW and DW are next to each other and pulsate in opposite phase. All other moving tissues move in phase with the nearest CCA wall. Distance between PW and DW can be assumed to be always between 4 to 10 mm from each other [9]. In summary, we search for a pair of prominent echoes, next to each other and are between 4 mm and 10 mm apart with negatively correlated motion.

We perform standard peak detection on e to get prospective wall locations and get pairs of peak locations that are adjacent to each other and are more than 3 mm apart. If there are T such pairs, we store the sample locations in P_e matrix with T rows (4).

$$\mathrm{P_e} = \begin{bmatrix} p_{1,1}, p_{1,2} \\ p_{2,1}, p_{2,2} \\ \dots \\ p_{\mathrm{T},1}, p_{\mathrm{T},2} \end{bmatrix}_{\mathrm{T}\times 2} \qquad (4)$$

At any peak location $p_{t,j}$ we choose a region of interest (ROI) over each frame in F_k given by (5).

$$\mathrm{R}_{n,t,j} = f_n\left(p_{t,j} - M, p_{t,j} - M + 1, \dots, p_{t,j} + M\right)$$
$$where, n = k - \mathrm{U} + 1, k - \mathrm{U} + 2 \dots, k \qquad (5)$$
$$t = 1, 2, \dots, \mathrm{T}\ and\ j = 1\ or\ 2$$

For each peak location $p_{t,j}$ we find the shift array $s_{t,j}$ having U-1 points given by (6) (fig. 3(d)). Shifts are found by searching for maxima of correlation between ROIs [1].

$$s_{t,j}(n) = shift\ between\ \mathrm{R}_{n,t,j}\ and\ \mathrm{R}_{n-1,t,j} \qquad (6)$$

$where\ n = k, k-1, \ldots k-U+2$

Thus, we have T pairs of shift arrays with U-1 points each. We find the inter-pair spearman correlation for each pair of shift array. We use the spearman correlation as we are only concerned with direction of shift and not their exact magnitudes which might be different due to difference in pressure around PW and DW. The pair with highest negative correlation value is declared as the PW and DW (7). If T = 0 or none of the shift pairs are negatively correlated we assume that the frame doesn't have a CCA and we declare that artery couldn't be found.

$$\mathrm{PW} = p_{t,1}\ and\ \mathrm{DW} = p_{t,2} \quad (7)$$
$$if\ corr(s_{t,1}, s_{t,2}) < corr(s_{k,1}, s_{k,2})\ \forall\ k \neq t\ and$$
$$corr(s_{t,1}, s_{t,2}) < 0$$
$$where\ corr(x,y)\ refers\ to$$
$$spearman\ rank\ correlation\ of\ arrays\ x\ and\ y.$$

VI. Validation

We recorded A-mode frame sequences from CCA of 30 human volunteers, 15 males and 15 females. A sequence of 500 frames was extracted from each dataset, where CCA could be clearly identified by a trained operator observing its characteristic motion. The observed location of PW and DW were stored as PW_o and DW_o. A test-bench was written in MATLAB® which used the above algorithm for identification of CCA in the frame sequence by using different number of frames (U). The result was said to be a HIT if algorithm was able to find the CCA in the frame. The automatically measured proximal and distal wall locations are given by PW_a and DW_a. It is a False Positive if artery was found but $|PW_a - PW_o| > M$ or $|DW_a - DW_o| > M$. Hit-rate (HR) was given by (8a) and False-rate (FR) was given by (8b). Percentage of correct estimates (CR) is given by (8c).

$$\mathrm{HR} = \frac{\text{No. of Hits} \times 100}{\text{No. of Trials}} \quad (8a)$$

$$\mathrm{FR} = \frac{(\text{No. of False Positives} \times 100)}{\text{No. of Hits}} \quad (8b)$$

$$\mathrm{CR} = \mathrm{HR} \times (1 - \mathrm{FR}/100) \quad (8c)$$

A False detection will mean that tracking of walls for measurement ofs distension will be initiated at a wrong location which can be detected only after few seconds of tracking by observation of anomalous distension waveform. For faster and more reliable measurements FR should be very low. Fig. 4 shows the results for combined mean values for HR, FR and CR for all datasets obtained by employing different values for U per measurement. Algorithm was first ran on raw frame sequences without pre-processing step (section IV) for which HR, FR and CR are given by $\mathrm{HR_{np}}, \mathrm{FR_{np}}$ and $\mathrm{CR_{np}}$ respectively and the results were compared with the detection rates for pre-processed frames ($\mathrm{HR_{wp}}, \mathrm{FR_{wp}}$ and $\mathrm{CR_{wp}}$) (fig. 4). HR and CR rise steeply for increment in U from 1 to 10 but no appreciable increase is seen above U = 10. $\mathrm{CR_{wp}}$ is 6% higher than $\mathrm{CR_{np}}$; this clearly demonstrates the efficacy of the pre-processing step. CR above 70% could be achieved with FR always remaining below 6%.

Thus, this algorithm can be suitably employed in an A-mode ultrasound system like ARTSENS to provide assistance to the operator in locating the CCA and automatically identify PW and DW.

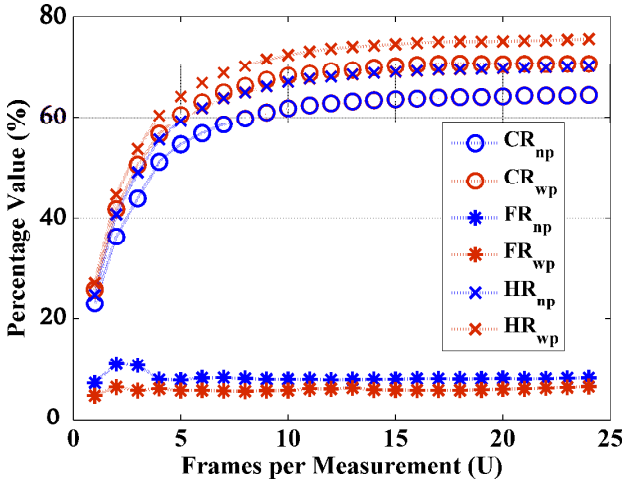

Fig. 4. Mean Hit-rate, mean False-rate and mean Correct-rate for automatic wall detection performed on datasets obtained from 30 volunteers. The mean correct-rate is higher by 6% for pre-processed frames

References

[1] J. Joseph and V. Jayashankar, "A virtual instrument for automated measurement of arterial compliance," *Journal of Medical Devices*, vol. 4, pp. 045004.

[2] E. Bianchini, C. Giannarelli, F. Faita, K. Raimo, V. Gemignani, L. Ghiadoni, and M. Demi, "The assessment of local arterial stiffness from ultrasound images," presented at Computers in Cardiology, 2007, 2007.

[3] P. J. Brands, A. P. G. Hoeks, J. Willigers, C. Willekes, and R. S. Reneman, "An integrated system for the non-invasive assessment of vessel wall and hemodynamic properties of large arteries by means of ultrasound," *European journal of ultrasound*, vol. 9, pp. 257-266, 1999.

[4] A. C. Rossi, P. J. Brands, and A. P. G. Hoeks, "Automatic recognition of the common carotid artery in longitudinal ultrasound B-mode scans," *Medical image analysis*, vol. 12, pp. 653-665, 2008.

[5] A. P. G. Hoeks, P. J. Brands, F. A. M. Smeets, and R. S. Reneman, "Assessment of the distensibility of superficial arteries," *Ultrasound in medicine & biology*, vol. 16, pp. 121-128, 1990.

[6] A. K. Sahani, J. Joseph, and S. Mohanasankar, "Evaluation of the algorithm for automatic identification of the common carotid artery in ARTSENS," *Physiological Measurement*, vol. 35, pp. 1299, 2014.

[7] M. Shah, J. Joseph, and M. Sivaprakasam, "Ultrasound Signal quality parameterization for image-free evaluation of arterial stiffness," accepted for presentation at Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE.

[8] A. K. Sahani, J. Joseph, and M. Sivaprakasam, "Automatic measurement of lumen diameter of carotid artery in A-Mode ultrasound," presented at Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE.

[9] M. S. Markert, D. Della-Morte, D. Cabral, E. L. Roberts Jr, H. Gardener, C. Dong, C. B. Wright, M. S. V. Elkind, R. L. Sacco, and T. Rundek, "Ethnic differences in carotid artery diameter and stiffness: The Northern Manhattan Study," *Atherosclerosis*, vol. 219, pp. 827-832.