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Toward Automatic Measurement of Carotid Blood Velocity

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Abstract—**The measurement of blood velocity in carotid is an important exam routinely performed in clinical practice. With the help of B-mode imaging, the operator places the Doppler sample volume in the carotid lumen, before switching the scanner to pulsed wave Doppler mode. Currently, only trained operators are able to carry out these operations by using expensive and complex systems. Unfortunately, points of care dislocated in rural areas or in developing countries often miss trained personnel. In this work, an automatic blind procedure for assessing the angle-corrected blood velocity in the carotid artery is proposed. The carotid position is detected through automatic, real-time segmentation of B-mode images, while a Doppler investigation from 2 different directions produces angle-corrected velocity estimation. The procedure was experimented on the ULA-OP research scanner, but it is shown suitable to be integrated in low-cost embedded electronics. Experiments on flow phantoms and volunteers show the efficacy of the method.**

Keywords- Doppler measurement; Blood velocity; Vector Doppler; Automatic carotid segmentation.

I. INTRODUCTION

Common carotid artery blood flow investigation is one of the most common ultrasound exams [1]: it is used, for example, to monitor the general hemodynamic conditions and to check for the presence of dangerous atherosclerotic plaques [2] in patients. The exam is carried out by an expert sonographer in few basic steps. Firstly, the operator searches for the correct probe position on the patient neck by checking the live B-mode image on the scanner. Then, he locates the region of interest (ROI) in the middle of the carotid lumen, places the M-line and the sample volume, and finally switches the scanner to the Echo-Doppler modality to get velocity data. Such procedure requires the presence on site of an expert sonographer.

Recently, the use of ultrasound techniques has diffused from hospital clinical facilities to peripherical health-centers and local points of care. The availability of compact and economical ultrasound systems [3], together with simplified ultrasound methods that can run on those apparatuses [4][5], may contribute to foster this change. Unfortunately, the availability of these apparatuses is often not sufficient, because of the sporadic lack of presence of trained personnel that can run the exams, especially in rural areas.

In this paper we present a method for the automatic detection of the carotid blood velocity. The method is based on the automatic segmentation of the carotid artery lumen in the B-mode live image. The user (not necessarily an expert professional) is requested only to place the probe on the patient neck so that it crosses transversally the carotid artery. This operation can be easily performed without the help of B-mode images. The acquisition procedure lasts few seconds, and then the angle-corrected velocity data can be sent to a remote center to be checked by a medical doctor.

The method was implemented on the ULA-OP research scanner [6] and tested on both flow phantom and on healthy volunteers.

II. MATERIALS AND METHODS

A. Probe geometry

The geometry of the probe used in this work is sketched in Figure 1. It is composed by 2 parallel arrays 31 mm wide (Array A and Array B), separated by 14 mm. Each array features 128 transducer elements. The arrays are angled by 40° so that their ultrasound beams cross at a depth of about 20 mm, corresponding to the typical position of the carotid artery.

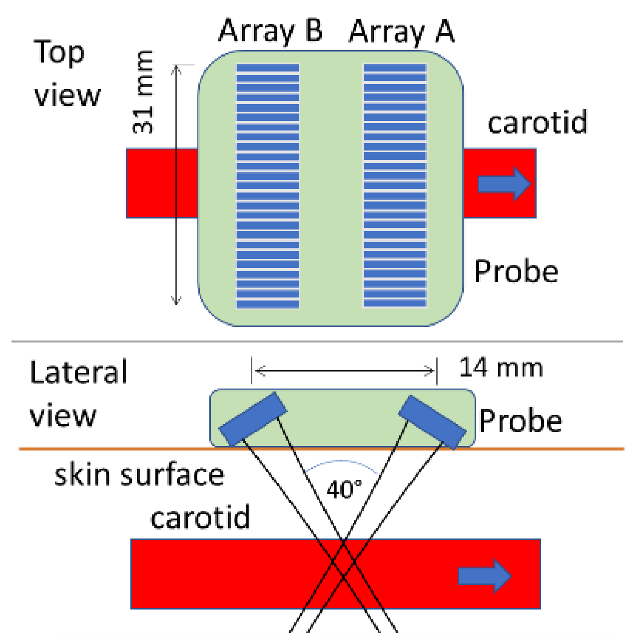

Figure 1: The proposed probe is composed by 2 linear arrays of 31 mm lateral extension spaced by 14 mm. The arrays are angled to form a 40° inter-angle.

The lateral dimension of the array was chosen so that it corresponds to the minimum size sufficient for the operator to have good chances to intercept the artery during a blind positioning. This value was selected through a study performed by testing a blind positioning with different apertures of a linear array. The convergent inclination of the two arrays allows to investigate the blood flow from 2 different directions, making it possible the automatic Doppler angle compensation through a dual beam approach [7] [8].

B. Detection of carotid position

A B-mode frame sequence is acquired from the 2 arrays. The aim of the method here described is to detect the lateral position of the carotid lumen when the arrays are set transversally to the vessel. The lumen is relatively easy to locate: it appears like a dark anechoic region surrounded by tissue with different echogenicity, which is typically clearer. Since the array inclination, a perfectly cylindrical vessel actually produces an elliptical shape, but the ellipticity is low enough that the section can be safely approximated to a roughly circular shape.

In summary, the method must locate a dark circle in a background of variable grey levels. We developed an algorithm based on the Circular Hough Transform (CHT), a well-established method for detecting curves and shapes in images [9] [10]. The algorithm proceeds as follows: for each frame of the B-mode sequence, the image is pre-elaborated to optimize the brightness and contrast. Then a strong Gaussian filter reduces the noise. Although several thin morphological structures are destroyed in this process, we found it beneficial to emphasize the artery lumen (see Figure 2). Then the CHT detects all the dark circles whose radii are within a resonable range. The detected center coordinates (x_i, y_i) and radii (r_i) are collected. For each of the dark circles that have been detected, the brightness values of their pixels are assessed. The circle showing the darkest values, i.e. the minimum brightness, is elected as "candidate circle", and its center (x_{ci}, y_{ci}) coordinates with radius (r_{ci}) are saved in a matrix of possible candidates. Once all the B-Mode frames sequence has been processed, the matrix holds the results obtained from each image. The most frequent (x_c, y_c, r_c) triad occurring in the matrix is selected as the final choice (red circle in Figure 2.D).

C. Flow measurement

Once the lumen center is located by the previous steps, for both arrays an M-line is placed across the lumen center, where the sample volume is located as well (yellow line in Figure 3). Doppler transmissions are alternated between the 2 lines, and data are processed through coherent demodulation [11], clutter filter, and spectral analysis, to obtain the Doppler shifts f_{dr} and f_{dl} from the right and left probe respectively. The Doppler shifts are triangulated to obtain the velocities along lateral (V_x) and axial (V_z) directions:

$$V_x = \frac{c}{2f_{tx}} \frac{f_{dr} - f_{dl}}{\sin\theta_{rx}}, V_z = \frac{c}{2f_{tx}} \frac{f_{dr} + f_{dl}}{1 + \cos\theta_{rx}} \quad (1)$$

where c is the sound velocity, f_{tx} the transmission frequency, and θ_{rx} is the receiving angle. The angle corrected velocity is finally obtained as:

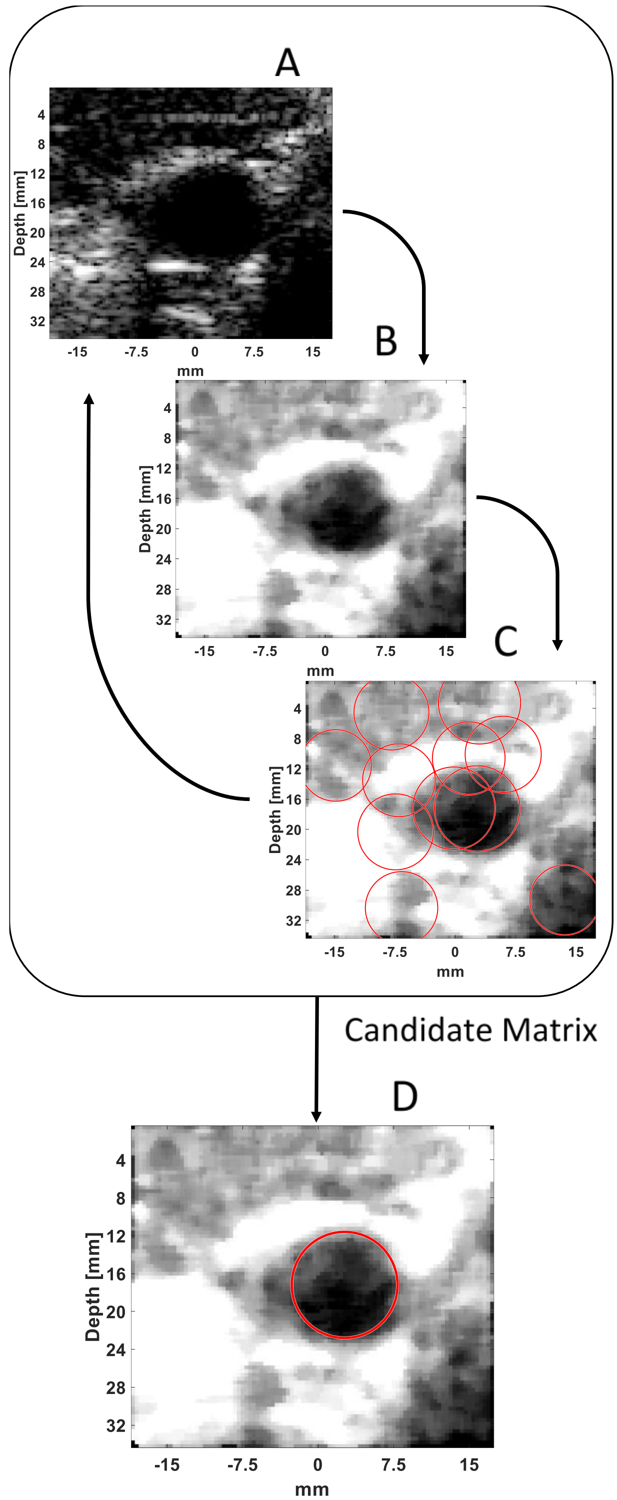

Figure 2. Automatic carotid segmentation procedure. A: the raw B-Mode image is acquired; B: the image is pre-processed; C: candidate carotids (red circles) are detected; A-C is repeated over 10 images to obtain the candidate matrix; D: The final segmentation is selected.

$$V = \sqrt{V_x^2 + V_z^2} \tag{2}$$

D. Scanner integration

The proposed method was integrated in the experimental open scanner ULA-OP [6]. ULA-OP was connected to Matlab (The Mathworks, Natick, MA, USA), which, through a proprietary interface, sets the parameters, starts/stops the acquisitions, gets and processes the data in quasi-real time. A Matlab script was coded so that it activated the B-mode acquisitions and downloaded the image sequence. It applied immediately the detection algorithm on the images that located the carotid center. The running script reprogrammed ULA-OP for Doppler investigation with the sample volumes in the detected position and started the acquisition for 2-3 cardiac cycles. Finally, it downloaded Doppler data and processed them for velocity detection. All the sequence lasts no more than 4s.

III. Experiments and Results

Phantom and preliminary *in-vivo* experiments on the common carotid artery (CCA) of healthy volunteers have been performed. In both cases, two linear arrays (LA533, Esaote S.p.A., Florence, Italy) have been arranged on a support with an inter-angle of 40° according to the geometry of Figure 1. Since ULA-OP cannot accommodate both probes simultaneously, the Matlab script was modified to add a 3s pause to let a second operator to commute the arrays when required. This operation did not influence the probe holder, which remained untouched in its position. For the experiments the scanner was set with the parameters reported in Table I.

During the experiments, in addition to the results of the automatic positioning, raw B-mode images and Doppler data were saved to be analyzed off-line. The saved images were processed by an expert operator who manually segmented the artery and selected the lumen center, i.e. the position where the sample volume should be placed for Doppler measurement. Manual segmentations, and in particular the sample volume positions were compared to those selected by the on-line automatic procedure with the metric:

$$De_i = \frac{1}{N} \sum_i \sqrt{(C_{Mxi} - C_{Rxi})^2 + \left(C_{Myi} - C_{Ryi}\right)^2} \tag{3}$$

$$PErr = \frac{1}{N} \sum_i De_i \tag{4}$$

$$PCV_{\%} = \frac{\mathrm{std}(De_i)}{PErr} \cdot 100 \tag{5}$$

where $\left(C_{Mxi}, C_{Myi}\right)$ and $\left(C_{Rxi}, C_{Ryi}\right)$ are the (x,y) coordinates of the measured and reference centers of the carotid lumen in the measurement i, De_i is the error distance, $PErr$ is the mean position error, $PCV_{\%}$ is the relative coefficient of variation. In case of distance error larger than 2 mm, the measurement was considered unsuccessful and was discarded.

Doppler data saved from both the arrays were processed through coherent demodulation, wall filtering, spectral analysis. Doppler frequencies were extracted by calculating the centroid of each spectrum and used in (1) and (2) to obtain the angle corrected velocity. The velocity was compared to the reference imposed by the pump with the metric:

$$VErr_{\%} = \frac{1}{N \cdot V_M} \sum_i (V_{Mi} - V_R) \cdot 100 \tag{6}$$

$$VCV_{\%} = \frac{\mathrm{std}(V_{Mi})}{V_M} \cdot 100 \tag{7}$$

where V_{Mi} and V_R are the measured and reference velocities, respectively, N the number of measurements, std($\cdot$) is the standard deviation, V_M the mean measured velocity.

A. Phantom experiments

A tissue mimicking Doppler flow phantom (524, ATS Laboratories) was used for the experiments. A gear pump moved a blood mimicking fluid in a 6 mm diameter pipe at a steady peak velocity of 20 cm/s. The operator, without the help of the ULA-OP display, placed the probe in a random position above the pipe of the flow phantom, then triggered the measurement in the echograph by starting the Matlab script. Once the procedure was completed, the operator removed the probe and placed it again in a new random position, repeating the measurement for N = 10 times. B-mode images and velocity data were saved for post-processing data elaboration. In the experiments the pipe center was located successfully in 100% of the experiments with a spatial accuracy of $PErr$ = 0.04 mm and a variability $PCV_{\%}$ of 0.3 mm. The velocity measurements resulted in $VErr_{\%}$= -2.3% and $VCV_{\%}$=3.4%. Results are summarized in Table II.

TABLE I
PARAMETERS EMPLOYED IN EXPERIMENTS

Parameter	**Value**
Probes Type	Linear
Element Pitch	245 µm
Bandwidth	6-11 MHz
Packet Size	128
TX/RX Aperture	16 elements (3.9 mm)
TX Azimuthal Focus	20 mm
Transmission	3 sinusoidal cycles @ 6.25MHz
Reception Focus	Dynamic focusing $F_{\#}$=3
Clutter filter	100 Hz

TABLE II
RESULTS OF THE MEASUREMENTS

Parameter	**Value**	
	Phantom	**Volunteers**
	Carotid segmentation	
Successes	100%	90%
$PErr$	0.04 mm	0.3 mm
$PCV_{\%}$	0.3 mm	0.3 mm
	Angle corrected velocity	
$VErr_{\%}$	-2.3%	-
$VCV_{\%}$	3.4%	11%

B. Volunteers test

Left and right carotid arteries of 2 healthy volunteers were investigated 3 times with the proposed automatic procedure, for a total of 12 measurements. The operator found the approximated position of the carotid by sensing the heart pulsation on the skin surface and accordingly positioned the probe. The operator was not allowed to look at the live B-mode display. When the operator was confident with the position, the automatic procedure started. B-mode images and Doppler data were saved for checking the results.

Figure 3 shows an example obtained from one of the volunteers. The carotid segmentation (red circle) and the M-line used for Doppler investigation (yellow segment) are superimposed to the B-mode image, displayed after the pre-processing. The carotid lumen center was located successfully in all the measurements, except one (about 90% of success). We obtained $PErr$ = 0.3 mm and a variability $PCV_{\%}$ of 0.3 mm in center lumen localization. Since the non-availability of a reference for in-vivo blood velocity assessment, the accuracy was not calculated, however the variation was $VCV_{\%}$=11%. Results are summarized in Table II.

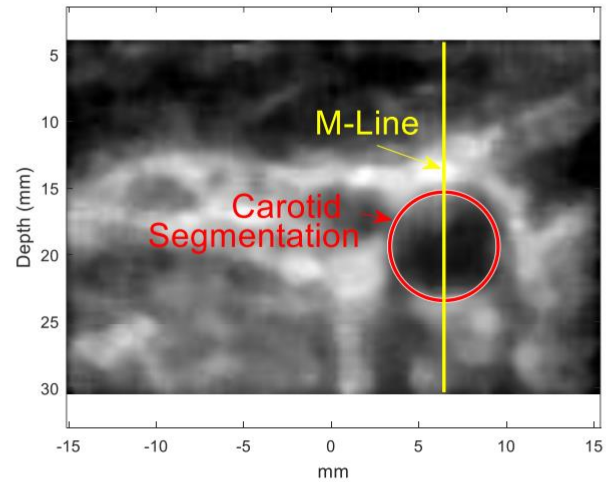

Figure 3. Pre-processed B-Mode image with superimposed the carotid segmentation (red circle) and the M-line (yellow) automatic positioned across the lumen center.

IV. CONCLUSION

A method for automatic detection of carotid lumen position and angle-corrected velocity measurement was presented. The method, although it was experimented on a complete research scanner [6], is targeted to be used by non-trained operators on portable, low cost ultrasound devices. The method can be useful also for long-time monitoring of blood flow [12] or clinical applications [13]. A low-cost, compact custom probe with integrated electronics is currently under development using Piezoelectric Micromachined Ultrasonic Transducer (PMUT) technology [14].

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