Real Time Assessment of the Endothelial Function

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Abstract

The endothelial dysfunctiom is a systemic marker of cardiovascular disease and it can predict the development of overt atherosclerosis. An ultrasound approach can be used to measure the endothelial function for non-invasive in vivo applications. Endothelium-dependent relaxation can be assessed by continuously measuring the brachial artery diameter change in response to occlusion and reflow. The main goal of this work is the development of an automatic and operator independent procedure which is able to locate the walls and to record, in real time, the diameter of the brachial artery. The localization procedure is based on the computation of the mass center of the first order absolute moment (FOAM). Important features of this operator allow parallel and real time implementation of the contour tracking procedure on DSP architectures. Methods derived from the standard regularization theory are also used to cope with noise and each wall is approximated with a straight line. The procedure was quantitatively assessed by computing the linear regression between the diameter estimated by the system and the diameter estimated by an expert.

1. Introduction

Endothelium has been recognized as playing a central role in the regulation of vasomotion [1]. The health of the endothelium can be evaluated by measuring its response to an endothelial directed vasodilator. Our task is to automatically compute the diameter of an artery during an endothelium dependent vasodilatation. This approach requires high quality acquisition equipment and an automatic analysis system which is able to process a large quantity of data. In this paper we choose a B-mode ultrasound imaging system since this method is non invasive and provides high resolution images. The ultrasound system is connected to a Windows NT based Personal Computer equipped with a Texas Instrument 'C80 Software Development Board' (SDB). The DSP board performs the following operations in real time. It captures the image at 25 frames/sec, localizes the vascular walls, computes the diameter, and transfers the results to the Personal Computer. The localization procedure is based on the computation of the mass center of the first order absolute moment (FOAM) since important features of this operator allow the implementation, in real time, of the contour tracking procedure. In order to cope with noise an appropriate regularization procedure has also been developed.

2. Methods

2.1. Image acquisition

The non-ivasive determination of the endothelial dysfunction was performed according to the method described by Celermajer et al. [2]. Brachial artery ultrasonography was used to measure the flow-mediated dilatation (FMD) as a marker of the endothelial function. The flow-mediated and endothelium-dependent relaxation was non-invasively assessed in vivo by continuously measuring the diameter changes of the brachial artery during hyperemia in response to occlusion and reflow. The brachial artery diameter was measured on B-mode images generated by a high-resolution ultrasound system. The measurements were taken at rest, during reactive hyperemia (endothelium-dependent vasodilation), and after the sublingual administration of glycerol nitrate (endothelium-independent vasodilation).

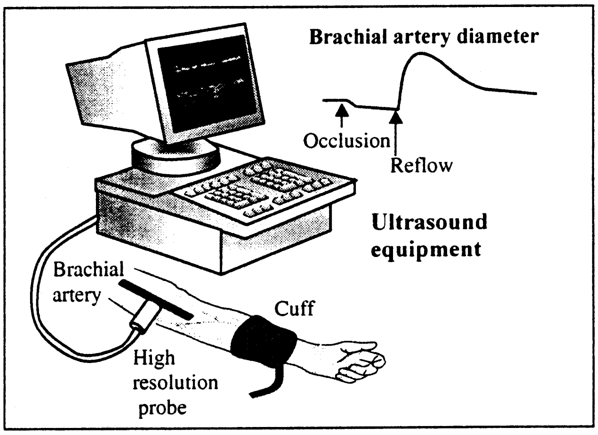

Figure 1: A high resolution ultrasound system measures the flow-mediated dilation of the brachial artery.

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Once the transducer was placed in the optimum position and with the clearest pictures of the anterior and posterior intima layers, the position of the transducer was marked on the skin and the arm was kept in the same position during the entire procedure. A mechanical apparatus was also used to support the probe in order to avoid any hand movement of the physician during the acquisition phase.

2.2. Contour tracking

The localization procedure is based on the computation of the first order absolute moment (FOAM) [3]. The FOAM is a dispersion index which is computed within a circular neighborhood of the image. It measures the difference between the mean value of the gray levels of the central pixels and the gray levels of the surrounding pixels. In this section, the edge localization properties of the operator are briefly described.

Let $f(n,m)$ be the gray level map of an image and let Θ_1 and Θ_2 be two circular neighborhoods of a point with coordinates (n,m). The FOAM is computed as follows:

$$e(n,m)=\sum\sum_{\Theta_2}\left|f_1(n,m)-f(n-k,m-l)\right|g_2(k,l)$$

where $f_1(n,m)$ is computed as

$$f_1(n,m)=\sum\sum_{\Theta_1}f(n-k,m-l)g_1(k,l)$$

and $g_1(k,l)$ and $g_2(k,l)$ are two Gaussian weight functions with a unitary summation on Θ_1 and Θ_2, respectively.
Let Γ be a vector with components k and l. We will call "FOAM mass center" the mass center of the gray level variability which is obtained by computing vector **b**(x,y):

$$\mathbf{b}(n,m)=\begin{cases}\dfrac{1}{e(n,m)}\sum\sum_{\Theta_2}\left|f_1(n,m)-f(n-k,m-l)\right|\Gamma g_2(k,l) & \text{if } e(n,m)\neq 0\\ 0 & \text{if } e(n,m)=0\end{cases}$$

Let us consider a gray level discontinuity and let us compute vector **b** at a point p with a distance d from the discontinuity. If the right configuration of the operator is chosen then vector **b** provides a mass center p' which is closer to the discontinuity than p, independently of the distance d. Therefore, given an approximate starting contour Cs of the discontinuity then the discontinuity can be located by iteratively computing vector **b** at the points of Cs. When any new iteration occurs, the new starting points are the mass centers which have been determined by means of the previous iteration. Three iterations were enough to locate the contours of the gray level discontinuities both of the synthetic and clinical images which we used to test the procedure [4]. Moreover, when dealing with image sequences, once the contour is determined on the first image it can be used as the starting contour to determine the contour on the subsequent image and so on. Therefore, when an approximate starting contour is given on the first image, every contour of the sequence is automatically outlined. The entire contour tracking procedure can be also easily implemented on DSP architectures in order to obtain real time performances [5][6].

2.3. Regularization stage

As we have seen in the previous section the boundary localization procedure is based on the computation of the mass center of the first order absolute moment. This operator is an efficient edge detector which can be used to locate the gray level discontinuities of an image.

Let Cs_u and Cs_l be two approximations of the upper and lower walls of the vessel, respectively. The borders of the vessel can be localized by iteratively computing the mass centers of the first absolute moment at the points of Cs_u and Cs_l.

However, due to speckle noise and artifacts of the imaging process, the contour tracking procedure frequently fails on echographic images. The problem is well known in literature and the procedure must be regularized [7][8]. For this reason, additional constraints were added to the movement and to the shape of the vessel borders. When the endothelial function is being assessed, the diameter of the brachial artery is computed by taking into account a narrow region of the vessel. The stretch of vessel in interest can be approximated by a cylinder and the two borders of the longitudinal section of the vessel can be approximated by two straight parallel segments. This strong constraint remarkably increased the robustness of the contour tracking procedure which can be summarized as follows:

- two straight parallel segments Cs_u and Cs_l are given as the approximate boundaries of the vessel on the first frame of the sequence,
- the mass centers of the first absolute moment are iteratively computed at N equidistant points of Cs_u and Cs_l,
- the borders of the vessel C_u and C_l are estimated by computing the linear regression of the two final sets of mass centers,
- the diameter d of the vessel is estimated as the mean distance between the points of C_u and the segment C_l,
- C_l is the new Cs_l and a straight segment parallel to C_l with distance d from C_l is the new Cs_u.

When this procedure was used the diameter of the vessel was correctly computed during the entire exam.

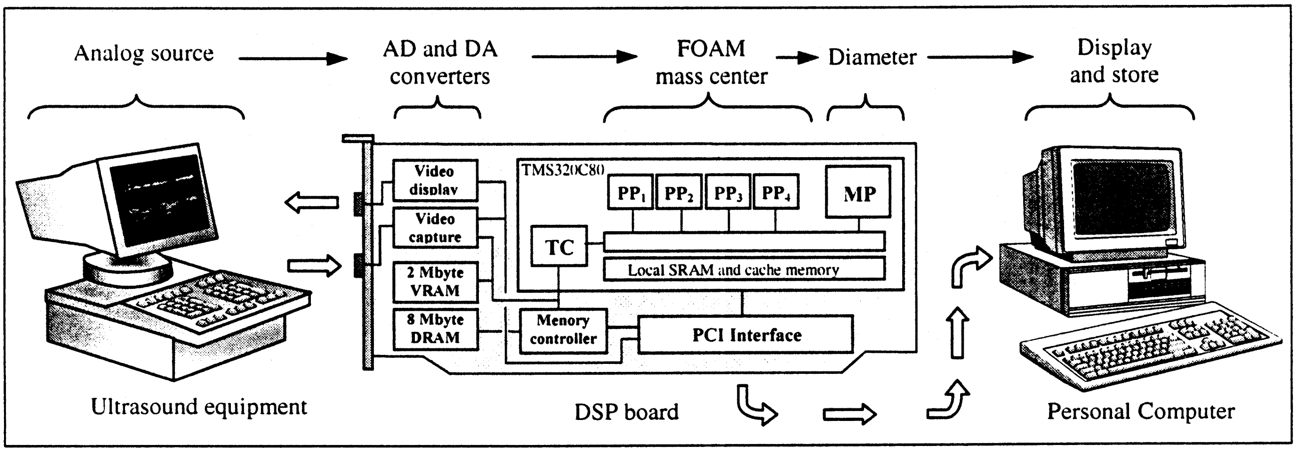


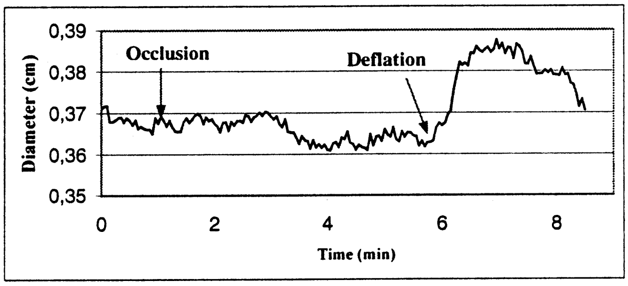
Figure 2: Architecture of the system

3. Architecture

An ultrasound system equipped with a high resolution transducer is used to acquire continuously the brachial artery images. The ultrasound system sends the video signal both to the automatic system and to a video cassette recorder. The procedures were implemented on a integrated software/hardware environment based on the interaction of a PC with a DSP board. The heart of the DSP board is the Texas Instruments TMS320C80 single-chip multiprocessor [9]. The TMS320C80 is a high performance and highly integrated digital signal processor especially designed to be used in image processing. The 'C80 architecture contains one master processor (MP) and four parallel processors (PPs). The DSP board can capture video signals at a rate of 25 frames per seconds with a resolution of 512x512 pixels, 8 bit per pixel. The computation of the FOAM mass center is implemented on the four PPs and executed in parallel. The algorithm is developed in assembler language in order to use all the capabilities of the PPs and to obtain real-time performances. The master processor manages the activities of the parallel processors and communicates with the external devices. Moreover, the MP computes the vascular diameter by using the edge information provided by the PPs and sends the computed value to the Personal Computer. The main task of the software running on the PC is to act as a user interface. The user interface is used to set up the parameters of the procedure and to start and stop the processes on the DSP. Once the procedure is running, the PC continuously receives the values of the vascular diameter computed by the DSP board. The diameter changes of the brachial artery are shown on the PC screen and stored on the hard-disk in real time. That is, the system allows us to monitor the diameter during the exam and, consequently, allows us to compute the clinical indices of the endothelial function in real time.

4. Application

The automatic contour tracking system was used in the clinical routine to assess the endothelial function. The timing of the automatic measurement was: 1' basal, 5' occlusion and 3' after reflow. The diameter was estimated by the system in real time during the acquisition phase and by an expert at the end of the exam. The automatic system was able to show the entire vasodilation curve and the typical indices: the average basal diameter, the value of the diameter at 60 sec after reflow, the time and the value of the diameter at the peak, the slope and the integral of the vasodilation curve.



(a)

Clinical Index	Value
Basal	0.368 cm
Diameter at 60 sec	0.388 cm
Peak diameter	0.391 cm
Time to peak	65 sec
Dilatation	6.25 %

(b)

Figure 3: An example of a normal response: (a) a curve of the diameter changes (b) clinical indices.

The accuracy of the procedure was quantitatively evaluated by computing the linear regression between the flow-mediated dilation, which had been estimated by the computer and the dilation which had been estimated by the expert. The results of the tests showed a good correlation between the automatic procedure and the manual approach (fig. 4). Usually the upper wall of the artery is less defined than the lower wall and speckle noise affects the images. When the regularization stage was not used the contour tracking procedure frequently failed. The regularization stage was needed to improve the performance of the procedure. When the regularization stage was used the system gave rise to localization errors only in the case of very inadequate image quality and when the image sequences were not stabilized. For this reason, a mechanical apparatus to support the patient's arm and the ultrasound probe was used to stabilize the acquisition phase and to allow small corrections of the probe position during the exam.

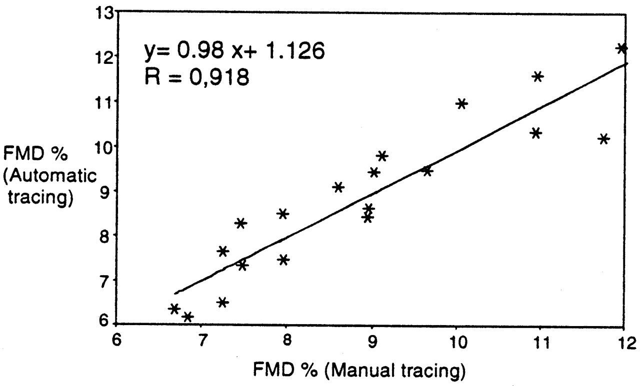


Figure 4: Correlation between the data provided by the automatic procedure and those provided by an expert.

5. Conclusion

The method described by Celermajer is a simple and non invasive method which is very useful for assessing the endothelial function. However, the measurement of the vasodilation requires the analysis of a large quantity of images. Therefore, the tedious and time consuming process of having to manually trace the vascular contours is unacceptable [10]. The system proposed in this paper speeds up the study of the endothelial function. Preliminary tests show the robustness of the method and the capability of the edge detector. The physician can also use the real time measurement of the diameter as a quality control parameter of the probe position during the acquisition phase. This procedure allows physicians to screen a larger number of individuals for endothelial dysfunction, particularly for follow-up and intervention trials, and reduces the variability between different laboratories.

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