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ULTRASOUND INVESTIGATION OF LARGE ARTERY MECHANICS

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Abstract - This paper presents an integrated system based on a programmable digital board specifically designed for real-time detection of both blood velocity profile and wall displacements in human arteries. Wall velocity is detected through the modified autocorrelation algorithm, while the blood velocity profile is obtained through spectral analysis. Preliminary applications of the new system, including the simultaneous analysis of blood flow and arterial wall movement in the common carotid arteries of a group of healthy volunteers, are discussed, and measurement results are presented.

1. Introduction

An altered large artery mechanics is associated to vascular aging and atherosclerotic disease. Physiologic indexes such as arterial distensibility, stiffness index and pulse wave velocity have an established prognostic value in predicting clinical complications of carotid, coronary, and renal atherosclerotic disease [1]

An accurate estimation of the vessel diameter and its changes throughout the cardiac cycle is one of the building blocks for obtaining such indexes. Most current approaches are based on the integration of estimated wall velocity. This is done starting from either the radio-frequency (RF) or the demodulated signal. The autocorrelation method with central frequency estimation has been shown to be an unbiased velocity estimator, mathematically equivalent to the RF complex cross-correlation [2,3,4,5].

Although several methods have been proposed in the literature, a few dedicated instruments have been so far introduced. This paper describes an integrated US system and its application to real-time detection of both the flow velocity profile and the wall movements in human elastic arteries. This system has been so far demonstrated capable of providing an accurate estimation of spectral Doppler components within human arteries (spectral profiles) [6]. Here, the extension of its processing capability to real-time estimation of arterial distension is described.

2. Material and methods

Experimental system

The heart of the system is a compact electronic card to be connected to an US front end, on one side, and to be plugged in a standard PCI slot of a PC, on the other side. The US front-end performs standard TX/RX functions such as RF burst signal generation, conditioning of received echoes and coherent demodulation. The experimental work described in this paper was performed by using the US front-end of a Megas commercial equipment (Esaote SpA, Florence, Italy), operating at 6.6 MHz.

The board is fed by the US equipment with the analog (I/Q) components of coherently demodulated RF echoes, and with a digital pulse replicating the transducer excitation rate at Pulse Repetition Frequency (PRF).

Analog signal acquisition is performed by means of two identical but independent input channels. The amplification and bandwidth of these channels are under the control of the DSP. The two channels feed independent 10 MSPS 14-bit ADCs whose sampling burst is issued by an FPGA EPF6016 (Altera Corp., San Jose, CA, USA). Since the PRF synchronism produced by the US equipment is uncorrelated to the DSP board, the necessary phase coherence between the US echoes arriving at PRF rate and the sampling clock, is reconstructed using a locked oscillator (LO) enabled by the PRF digital input.

128 samples for each pulse repetition interval (PRI) are temporarily stored in 32 MBytes of on board SDRAM and can be downloaded on disk when the acquisition settings yield good results.

Because of the large quantity of calculations and complex data management requested by the US application, the TMS320C6202 (Texas Instruments Inc., Dallas, Texas) has been chosen as on board DSP. The DSP processes the raw data gathered from the ADC.

Both raw data and processed data are sent to a PCI bridge through a 32 bit 40 MHz synchronous data channel.

Spectral profile detection

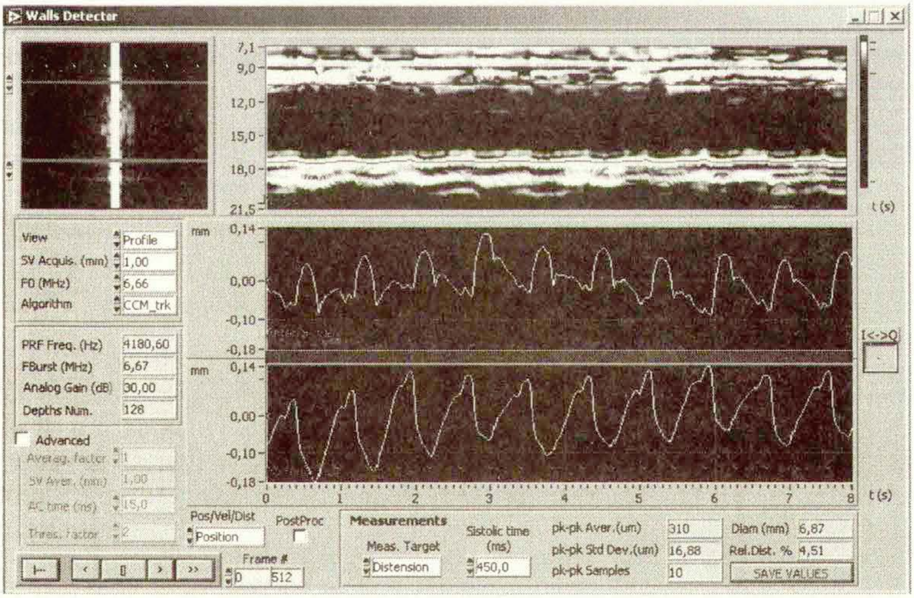
The basic application of the instrument is the study of blood flow inside the arteries accessible with the US technique. For this application, the processing applied to the backscattered signals consists in the assessment of the power spectral density for each depth by an optimized FFT algorithm. The result of this elaboration is the so called spectral profile, where the power spectral density is represented in color code, in function of frequency and depth. The velocity profile inside the vessel can be extracted directly from the spectral profile [6].

Wall detection

The first step, in order to process the signal generated from the wall echoes, is represented by the search for their approximate position. Since each wall contributes to at least one of the 128 samples taken for each PRI, the corresponding index must be found. Such goal is achieved in real-time through the combination of the classic tracking method [7,8] and the power gradient extreme search (GES).

The latter is started by handling the probe in such a way that the walls are intercepted by 2 gates which are located in the upper and lower halves of the spectral profile display, respectively. The A-mode signal and its gradient are then computed. Starting from the central (64-th) gate and moving back and forth, the gradient extremes are searched. The first gate corresponding to a local power gradient minimum (maximum) with a value lower (higher) than a given threshold is selected as indicating the starting anterior (posterior) wall position [9]. The correct instantaneous wall gate index is obtained by combining the low pass filtered GES estimate with a high-pass filtered version of the tracking estimate [3]. This hybrid algorithm rapidly finds the walls and effectively follows them during the heart cycle.

Wall velocity is estimated by autocorrelating the samples taken around the selected gate over subsequent PRIs. Autocorrelation along the time axis gives the phase shift relative to wall motion [10], and that done along the depth axis gives an estimate of the received pulse average frequency. The latter estimate is used to compensate for frequency-dependent tissue attenuation [2, 5].



View	Profile
SV Acquis. (mm)	1,00
F0 (MHz)	6,66
Algorithm	CCM_trk
PRF Freq. (Hz)	4180,60
FBurst (MHz)	6,67
Analog Gain (dB)	30,00
Depths Num.	128
☐ Advanced	
Averag. factor	1
SV Aver. (mm)	1,00
AC time (ms)	15,0
Thres. factor	2
Pos/Vel/Dist	Position
PostProc	☐
Frame #	0 512

Measurements

Meas. Target	Distension
Sistolic time (ms)	450,0
pk-pk Aver.(um)	310
pk-pk Std Dev.(um)	16,88
pk-pk Samples	10
Diam (mm)	6,87
Rel.Dist. %	4,51

Figure 1: Spectral profile (top-left), time motion display (top-right) and wall displacement curves of a healthy male volunteer as obtained from postprocessing software

3. Experiments

In vitro experiments

In vitro validation was carried out by using a machine that can generate a repeatable displacement of a plexiglas reflector. This machine is based on an elastic jointed beam whose free end is moved by a cam. The deformation line can be predicted by a linear model of the structure geometry. The cam, actuated by a motoreductor, creates an approximately sinusoidal displacement of 3.9 mm peak-to-peak amplitude, which is demultiplied by a factor 10 when the probe is placed at an appropriate distance from the joint. The overall repeatability (considering both mechanical inaccuracies and measurement system error and drift) turned out to be better than 1 μm.

In vivo experiments

"In vivo" tests were performed by measuring diameter and distension (systo-diastolic diameter change) of right and/or left common carotid arteries in 33 healthy volunteers. Mean age and age range for the overall group were 49.9±17.1 and 16-70 years, respectively.

During each measure, the Megas linear array probe was first held along the longitudinal vessel axis in order to roughly position the M-Line 2 cm distal to the bifurcation. The system was then switched to PW Doppler, and the most appropriate M-line orientation was found by checking the PC real-time display. In particular, for distension measurements, the symmetry of the spectral profile [11] and the quality of the displacement waveforms on the PC display were taken into account. When the operator evaluated that the best transducer position has been obtained, raw data covering at least 5 cardiac cycles was stored in the PC.

The distribution of distension and diameter estimates obtained in 50 explored arterial segments correspond to an average vessel diameter, D, of 7.25 mm (SD=1.09 mm) and average distension, ΔD, of 512 μm (SD=252 μm). The average SD of the distension amplitude measured for neighboring cardiac cycles was only 28 μm.

4. Discussion and Conclusion

This paper has presented a real-time system integrated in a home-made DSP board, allowing suitable processing of signals backscattered from blood as well as of signals reflected from arterial walls. Real-time operation is crucial in order to overcome the typical problems connected to a correct positioning of the US probe. By checking the spectral profiles and the wall displacements, the operator can easily optimize the transducer position. This allowed obtaining good signals from all volunteers, and no acquisition was discarded. In conclusion, the developed system is precise enough for assessment of arterial distension, and thanks to its real-time capability of detecting the flow velocity profile, may be used also for shear rate measurements. It thus represents a promising means for an integrated investigation of arterial mechanics.

Acknowledgement

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