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Experimental Blood Flow Investigations in Large Human Arteries

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Extension of classic spectral analysis to all Doppler signals backscattered along an ultrasound (US) M-line has been proved useful to provide detailed information on blood flow behaviour in major human arteries. Application of a 2D auto correlation processing method to the echo signals reflected from the arterial walls has allowed their elastic properties to be investigated, too.
This paper reviews some of the main activities developed at the Microelectronics Systems Design (MSD) Laboratory of the University of Florence with the aim of extracting valuable hemodynamic and mechanic information from the US M-line echo signals.

Key words: *Doppler ultrasound, velocity profiles, arterial mechanics*

1. Introduction

Ultrasound (US) non invasive investigations are capable of providing useful information on either the hemodynamics and the mechanics of large human arteries [1, 2]. To achieve simultaneously both pieces of information we have developed a real-time digital processing board, to be connected to an external US transmitter-receiver (TX-RX) unit.

Next sections report on the main features of such board and the complete experimental setup in which it has been used. Results of different applications are then reported, for hemodynamic investigations in the CCA and aorta, and for non invasive HCT measurement. Estimation of the board processing capability to simultaneous distension measurement is then described, and some examples of in vitro and in vivo experiments are reported.

2. Materials and Methods

The typical experimental setup used in our blood vessel investigations consists of either a custom made US transmitter-receiver (TX-RX) unit, or a commercial ecographic US machine (Megas, Esaote S.p.A., Florence, Italy), paired with a proprietary multigate acquisition processing board [3] (Fig. 1).

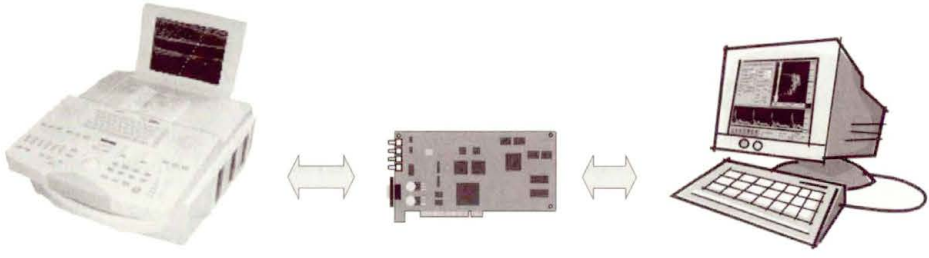

FIGURE 1. Experimental setup

When the ecographic apparatus is used, brightness mode (B-mode) imaging capability is exploited to explore the region of interest (ROI) and choose a single line of investigation (M-line) across the image. When the orientation of such line has been fixed, the pulsed wave (PW) mode is switched on. US bursts, focused along the selected line, are transmitted and received every pulse repetition interval (PRI).

The received echo signals are amplified and coherently demodulated to provide base band in phase/quadrature (I/Q) channels.

The multigate processing system is a PCI-bus plug in card, hosted in a PC. Such board first performs the required analogue conditioning of the base band signals coming from the US system. Such signals are then digitized with two 10 MSPS 14-bit ADCs, generating 128 digital complex samples for each pulse transmitted at the pulse repetition frequency (PRF=1/PRI) rate. This resolution is necessary to preserve the high input dynamic range due to the possible simultaneous presence of both strong and weak US echoes.

The dedicated real time signal processing is performed by a TMS320C6202 DSP (Texas Instruments Inc., TX) [3]. Elaborated data are sent to the host PC through the PCI bus for real time display. Raw data can also be stored on the PC hard disk.

The system is provided with a dedicated software on the PC that lets the user viewing in real time all the results of the signal processing, and reviewing raw data stored on the disk, to perform post processing operations and measurements.

I/Q signals coming from a selected gate are also processed in real time on the PC with a Hilbert transform based method [4, 5] that allows the separation of the Forward and Reverse (Fw/Rv) signal components (related to positive and negative velocities, respectly). Fw/Rv samples, produced at PRF rate are resampled [6] to match the digital audio standard formats (44.1 or 48 kHz) and played with a low latency (< 60 ms) on stereo speakers through the sound card of the host PC [7]. Audio data can also be saved on the hard disk in uncompressed (`.wav`) or compressed (`.mp3`) format [8]. All the audio signal processing is made in real time on the PC with a dedicated software, with no extra load for the DSP unit on the acquisition/processing board.

3. Hemodynamics Investigations

The multigate Doppler system is capable of giving precise information about the blood velocity distribution inside the vessel (velocity profile). The DSP elaborates the samples coming from different depths, with an optimized 128-point FFT algorithm, that generates, for each depth, the corresponding power spectral density. The result of this elaboration is the so called spectral profile, a matrix of 128×128 data, computed every 20 ms [9]. These spectral data are sent to the host PC and displayed in real time.

3.1. In vivo Test

Experimental investigations in human common carotid arteries (CCAs) have proved that the velocity profiles generally assume a parabolic shape during diastole and early systole, and become flat during the systolic peak. However there are some particular conditions in which the shape of the profile changes more appreciably: for example, during the deceleration phase when the velocity near the walls results higher than in the vessel center, and the profile assumes an "M" shape.

As an example Fig. 2 shows a typical spectrogram detected in the center of the CCA of a healthy volunteer. The velocity profiles corresponding to the time instants highlighted in vertical lines in the reference spectrogram

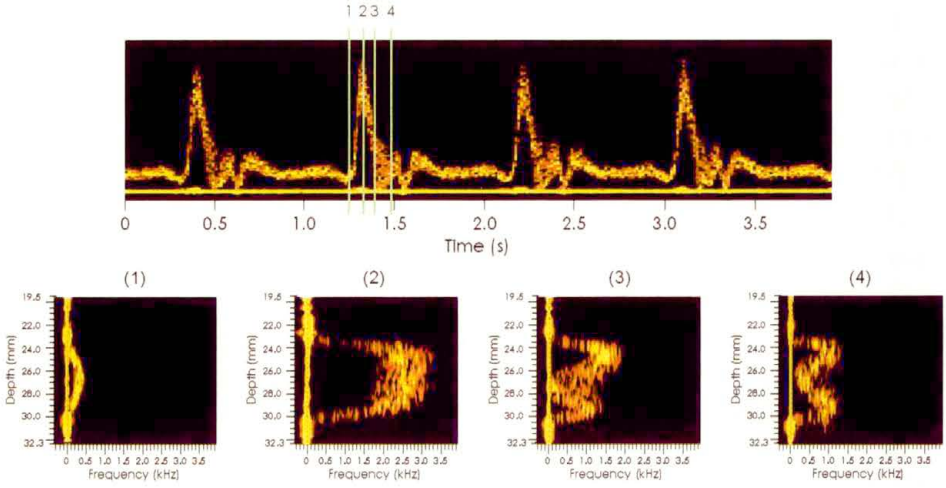

FIGURE 2. Shapes of the spectral profiles in different phases of the cardiac cycle. It can be noticed an asymmetric shape for profile #3 and an "M" shape for profile #4.

are also shown [9]. Frequency (i.e. speed) is here plotted on the X axis, and depth on the Y axis, while the intensity of the spectra are colour coded for each point.

The same acquisition system has also been used with a dedicate esophageal probe (Arrow International, PA, USA) to investigate the aortic blood flow. In vivo tests have been made in patients under general anaesthesia or in the intensive care area at the E. André hospital of Lyon, under the direction of

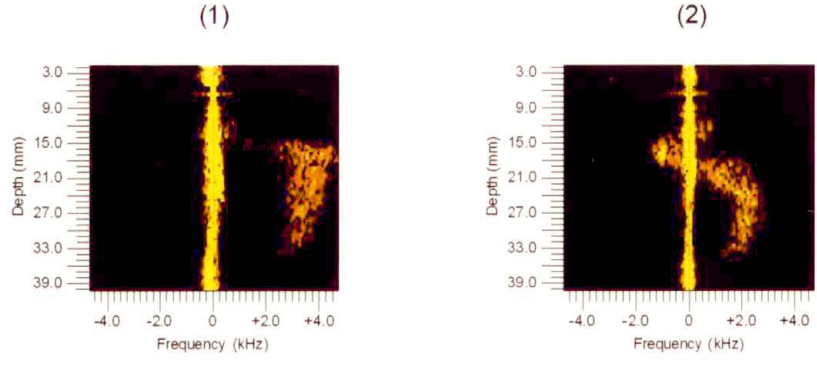

FIGURE 3. Instantaneous spectral profiles detected in the aortic artery. (1) during the systolic peak of the cardiac cycle; (2) during the systolic deceleration, in a location between the arch and the descending aorta.

Dr. R. Muchada. Such tests confirm that blood flow behaviour in the aorta is more complex than in CCA, especially at the level of the aortic arch or in not physiologic circumstances. Velocity profiles are flat during the systolic acceleration but not during the full cardiac cycle, showing in most cases an asymmetrical shape, including both positive and negative components (Fig. 3) [9, 10, 11].

4. Hematocrit Measurements

Doppler echoes can be conveniently used to measure the US attenuation in blood. Previous studies have shown a linear relationship between US attenuation and the hematocrit (HCT) [12, 13]. The attenuation coefficient can thus be used to determine the HCT, once the transmitting frequency is fixed and after a suitable calibration of the system is made.

Previous work used the echoes coming from two different gates inside the vessel [14], measuring the attenuation as the difference in the received power at such gates. However this method results too sensitive to the selected gates and suffers for a lack of stability and repeatability.

A new technique has been recently introduced, which evaluates the attenuation coefficient with a robust averaging method using echo-signals from all depths inside the vessel.

In vitro measurements have been done at the US Department of the IPPT-PAN, Warsaw, with samples of whole porcine blood and separated plasma with HCT ranging from 1% to 65% using a 20 MHz unfocused transducer. Steady and pulsatile flow conditions, similar to those existing in the brachial artery, have been simulated with a suitable pump.

The attenuation coefficient, determined by the reduction of Doppler amplitude with increasing depth, confirms the linear relation to hematocrit with a good correlation coefficient ($R = 0.992$ for pulsatile flow).

Preliminary application of the new estimation technique in a first group of 12 patients has produced encouraging results. The mean error has been of only 3% HCT, with a maximum error of 5% HCT.

5. Arterial Mechanics Investigations

In arterial mechanics investigations, the interest is not limited to blood flow, but extended to the movements of the vessel walls. The analysis of

such movements, in fact, can provide information on the arterial distensibility/stiffness, as related to atherosclerosis and vascular aging [15].

One of the goals in this analysis is the accurate estimation of the vessel diameter and its changes during the cardiac cycle. Approaches are currently based on the integration of estimated wall velocity. The latter is obtained using the autocorrelation method with central frequency estimation, which has been shown to be an unbiased velocity estimator [16, 17, 18].

The DSP-based system is capable of estimating the arterial distension simultaneously with the spectral profiles as described in the previous section.

5.1. Vessel Walls Identification

The estimation of instantaneous arterial walls positions during the cardiac cycle first needs a rough selection of the gates that actually include the wall echoes. Such selection is obtained in real time by combining the classic tracking method [19] with the power gradient extreme search (GES).

The US system has to be set up so that echoes from the two vessel walls are each in one half of the spectral profile display. The A-mode signal and its gradient are then computed: the gradient extremes are searched spanning back and forth from the central depth of the spectral profile (gate 64). The first gate corresponding to a local power gradient minimum (maximum) with a value lower (higher) than a suitable given threshold is selected as the starting anterior (posterior) wall position [19].

5.2. Tissue Motion Estimation

Tissue velocity is determined by processing the clutter signal, which is originated by the strong echoes coming from nearly stationary targets (walls). Samples taken around the wall gates over subsequent PRIs are self correlated. The self correlation along the slow time axis provides the phase shift relative to the wall motion [20, 21], while that one done along the depth axis provides an estimate of the received pulse average frequency. The latter estimate is useful to compensate the frequency dependent US attenuation [16, 18].

The described algorithm has been validated in vitro using a machine based on a precision linear actuator (T-LA-28S, Zaber Technologies Inc, Canada). This machine is capable of generating cyclic and repeatable displacements (peak to peak amplitude 610 μm) of a plexiglas plate carrying a sample of tissue mimicking material. We measured an average displacement of 607 μm,

with a global repeatability of less than 2 μm (including mechanical inaccuracies, measurement system errors and drifts).

Tissue motion estimation has been implemented to investigate the changes in the vessel diameter from the difference between systolic and diastolic diameter (distension) of the CCA.

A preliminary test has been performed on 33 healthy volunteers aging in the range of 16–70 years. For the measurements the optimal placement of the transducer has been achieved taking into account the symmetry of the spectral profile [22] and the quality of the displacement waveforms, displayed in real time on the host PC.

The average vessel diameter measured over 50 explored arterial segments was 6.9 mm (SD= 0.66 mm), while the average distension was 499 μm (SD= 188 μm). The intra-measure repeatability, expressed as the SD of the amplitude measured for the same volunteer in neighbouring cardiac cycles, was only 28 μm. As an example, Fig. 4, reports the displacement of both vessel walls (near and far) and the relative distension for subsequent cardiac cycles, in the CCA of one of the volunteers.

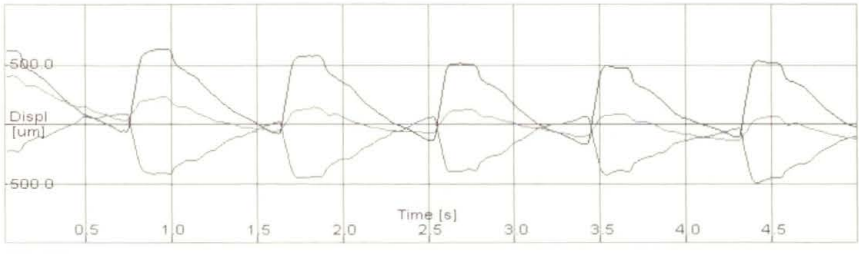

FIGURE 4. Displacement and distension in a CCA over several subsequent cardiac cycles. Upper line: distension; Middle line: near wall displacement; Lower line: far wall displacement.

6. Conclusion

This paper has reviewed the main applications of a real time US signal processing system implemented at the MSD Lab of the University of Florence.

Such system has been shown capable of providing significant information on hemodynamics of large vessels like the CCA and the aortic arch. More recently, the capability of investigating the mechanics of major human arteries has been added. The average diameter and distension measured in the CCAs of 33 healthy volunteers have been 6.9 mm and 499 μm, respectively.

The average standard deviation between distension measurements over consecutive cardiac cycles was only 28μm, thus showing the high resolution of the proposed method. Preliminary non invasive measurements of hematocrit have also been obtained. Although more measurements are necessary, the mean error measured in a first group of 12 volunteers was only 3% HCT, with a maximum error of 5% HCT.

The high programmability of the system makes it suitable for further applications currently under consideration.

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