Online measurement of cardiac indices from frequency transformed TAV Doppler ultrasound signals

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Abstract—A system is described for the analysis of blood flow signals in the aortic artery which enables indices of stroke volume and cardiac output to be derived. A commercial Doppler ultrasound monitor is used, the demodulated return signals are digitised, and frequency analysis is performed in real time using an FFT signal processing circuit. A Z-80 microprocessor controls the synchronisation of the data acquisition, transformation and display of the signals. Algorithms have been developed to identify the maximum velocity profile of each heartbeat and perform the necessary calculations to produce indices of stroke volume and cardiac output. The system has been evaluated against an existing offline method for a series of recordings on normal subjects and has demonstrated good repeatability. It has also been used in a clinical study on the effects of anaesthesia on chronic spinal injury patients. The results have shown that the system can be used to follow serial changes in cardiac performance within individual subjects.

Keywords—Cardiac indices, Doppler ultrasound, FFT, Microprocessor, Transcutaneous aortoveloagraphy (TAV)


1 Introduction

The technique of transcutaneous aortoveloagraphy (TAV) is a relatively simple method for obtaining information about cardiac blood flow (Light and Cross, 1972). It is a Doppler ultrasound technique in which a probe is placed at the top of the suprasternal notch and directed such that the ultrasound beam will intersect with the flow in the arch of the aorta as illustrated in Fig. 1. The beam is then back-scattered at a different frequency by the moving red blood cells according to the Doppler principle. An operating frequency of 2–3 MHz is used as the arch of the aorta is typically about 80 mm from the measurement site. The resulting Doppler frequency shifts fall well within the audible spectrum, e.g. at 2 MHz a velocity of 1 m s⁻¹ produces a frequency shift of approximately 2600 Hz. The optimum probe position is found by adjusting it until the maximum possible frequency output is obtained: this should correspond to mainstream flow in the aorta.

As the TAV measurement does not provide any information about the cross-sectional area of the aorta, an absolute value of stroke volume or cardiac output cannot be obtained. However, in certain clinical situations, it is of benefit to be able to follow changes in one individual caused, for example, by therapy or surgical intervention. A reliable index of stroke volume or cardiac output depends on assumptions that can be made about the velocity waveform. Some studies (Schultz et al., 1969; Goldberg, 1971) have indicated that the velocity profile across the aorta should normally remain constant in any one subject over lengthy periods of time; that this profile is essentially flat ('plug' flow) has also been shown to be a reasonable

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Fig. 1 Section through the thorax showing the relationship between the direction of the ultrasound beam and the arch of the aorta
assumption (Peronneau et al., 1974). Although the diameter of the aorta can increase by up to 10 per cent during the cardiac cycle, this need only be taken into account if an absolute measure of volume flow is required. Changes in the cross-section should be similar from cycle to cycle and will not affect trends in the stroke volume index as measured by the proposed system.

Blood flow in vessels neighbouring the aorta should normally have systolic velocities higher than that in the aorta, and the angle at which such vessels intersect with the beam will be greater than those from the aorta. As a result, the maximum frequency present at each instant during systole (the ‘maximum frequency envelope’) should provide a reasonable approximation to mainstream velocity in the aorta. Finally, as the fraction of the cardiac output which goes off to supply the heart, head, neck and arms can be assumed to remain constant (at about 20 per cent of total output (Cross and Light, 1974)) the TAV measurement should accurately reflect changes in the cardiac output.

It can be shown that the actual volume of blood pumped out on each heart beat (the stroke volume) is proportional to the product of the aortic cross-sectional area and the area under the maximum frequency envelope. Any changes in the stroke index value should therefore appear as changes in the area under this envelope. The cardiac output index is then calculated as the product of the stroke volume index and the heart rate. In addition to providing an audible output, most TAV systems incorporate some form of frequency analysis and real-time display of the signal. These frequency-analysed signals are usually recorded on hard copy, e.g. UV paper, and the area calculations are carried out offline. In the past this has been done manually by approximating the envelope shape to a triangle (with a typical error of 10 to 25 per cent (Sequeira et al., 1976)). Alternatively, a digitising tablet may be used: a number of points on the envelope are digitised and the calculation of area is done by a microcomputer. There are obvious advantages in using an online method of processing the signals and one system has been developed for pulsed Doppler blood velocity signals (Caprihan et al., 1982).

This paper describes a method for the online analysis of TAV signals using a Z-80 microprocessor and an AMI S2814A Fourier transform signal processing integrated circuit. The technical specifications of the system have been described previously (Franks and Lydon, 1984). A waveform analysis routine (Johnston et al., 1982) developed for Doppler blood flow signals has been modified and algorithms developed so that indices of stroke volume and cardiac output can be calculated and displayed. The system has been used in a clinical study of spinal injuries patients (Barker et al., 1985) and has been evaluated, using data from normal subjects, against an offline system.

2 Measurement system

A Sonicaid ‘Vasoflo’ Doppler velocimeter was used for all measurements. This is a 2 MHz continuous wave device and it provides not only the phase-separated forward and reverse flow signals but also the outputs from the sine and cosine mixers (the ‘quadrature’ outputs). These enable the FFT process to separate forward and reverse flow. The use of an angular rather than a straight probe makes positioning of the probe in the suprasternal notch easier. Fig. 2 shows a block diagram of the complete system.

The ‘wall thump’ filter (to attenuate low-frequency artefacts due to vessel wall movement) is a two-stage high-pass filter with a $-3\,\text{dB}$ frequency of 300 Hz and a $-24\,\text{dB}$ per octave roll-off. The antialiasing filter is a single-stage low-pass filter with a $-3\,\text{dB}$ frequency of 7.3 kHz and a $-12\,\text{dB}$ per octave roll-off. The $-3\,\text{dB}$ frequency was chosen so that there was no attenuation of blood flow signals close to 5 kHz, and on the assumption that there was unlikely to be large artefact between 5 kHz and 7.3 kHz. This was borne out in practice as no aliasing artefact was observed on the display. A thumbwheel gain control is used to prevent saturation of the analogue-to-digital converters, which would produce spurious high-frequency points at the output. The signals were recorded on magnetic tape using a ‘Racial Store 4’ tape recorder so that subsequent evaluation could be carried out.

The FFT chip is the S2814A (American Microsystem Inc.) and it is controlled by a Z-80 microprocessor. The signals are digitised at 10 kHz and 8-bit resolution. A Blackman-Harris window function (Harris, 1978) is applied to the input data before transformation to reduce high frequency artefacts associated with the use of a rectangular window. The Z-80 controls the transfer of data to and from the FFT chip and the display of the transformed data. The transformed data is displayed on a 256 x 256 point, 16 grey level display. The complete system has already been described in detail (Franks and Lydon, 1984).

The FFT chip can perform a 64-point complex transformation. If the two quadrature signals are used as the real and imaginary inputs, then the 64 output points will correspond to 32 forward and 32 reverse frequencies and they are spaced out at 156 Hz. This flow-direction separation comes about as a result of the symmetry properties of the Fourier transform process.

3 Analysis procedure

3.1 Production of real-time display

The output from the FFT chip appears as 64 frequency points, half of which represent reverse frequencies and half represent forward frequencies. For each transform the 32 reverse frequency points are examined to find the frequency point which has an amplitude value greater than a specified threshold: this is then taken as the maximum frequency value. The effect of varying this amplitude threshold is discussed in Section 4. The maximum frequency value is then stored in a 512 element sequential memory buffer. On each sweep across the screen a total of 256 output data blocks are displayed so that two complete sweeps of maximum frequency values are stored in the memory buffer. The time between each point block is 16 ms so that the stored data length corresponds to 8.2 s. This will average out effects on the signal due to respiration.

The display is arranged so that the reverse frequency points appear above a central, zero-frequency baseline and the forward frequencies appear below it. The frequency