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ORIGINAL ARTICLE

A computerized arterial graft monitoring system

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SUMMARY

Despite improvements in patient assessment and surgical techniques, a significant number of lower limb arterial grafts fail in the early postoperative period. Intervention can convert a failing into a successfully functioning graft, but relies on the early detection of graft deterioration. In order to address this problem we have developed a self-contained real time system, which provides ward staff with up-to-the-minute information about the flow and flow pattern in grafts. The system comprises an IBM compatible computer, a commercially produced AT&T DSP32C based signal processing board, and a purpose built CW Doppler transducer and board. The entire system is housed inside the computer, making a compact bedside monitor. It is extremely flexible and is easily configured for different applications. The system has been used to monitor a number of grafts successfully.

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INTRODUCTION

Atheromatous disease is a widespread condition which leads to a reduction in the diameter of arteries (stenosis) and sometimes to their complete occlusion. It may lead to ischaemia or infarction of the tissues supplied by the affected arteries. In the lower limbs occlusive atheromatous disease may lead to intermittent claudication, rest-pain, or even gangrene.

Since the medical treatment of vascular disorders is unsatisfactory, surgical procedures to improve blood supply may be considered. Deficient arteries are replaced by prosthetic or vein bypass grafts to restore normal blood flow. The early success of such bypasses is highly dependent on technique; but durability may be a function of many factors, including the diameter and length of the graft, the inflow source, and the outflow capacity.[1] The majority of grafts which fail do so immediately or within the first year of surgery. Intervention can convert failure into a successfully functioning graft but this requires the early detection of graft deterioration.[2] The introduction of graft surveillance programs has increased the long-term patency rate but the methods used for medium and long-term graft surveillance are not suitable for monitoring grafts in the immediate postoperative period when up to 20% of failures occur.

Early graft monitoring systems developed in our laboratory employed simple continuous wave (CW) Doppler units and tape recorders.[4–6] Raw Doppler signals were recorded in the theatre or ward and Doppler spectrum analysis performed retrospectively.[7] Whilst these systems gave useful information concerning the general behaviour of flow in grafts (both successful and failing) their usefulness in terms of affecting the outcome of a particular graft was extremely limited.

A graft monitor which is to fulfil this latter function needs to be able to perform spectral analysis and parameter estimation on-line in the theatre or ward with a minimum of human interaction. It should also be flexible enough to be easily modified when necessary and operational cost should be low. Keeping these essential requirements in mind, a computerized graft monitor has been developed and evaluated on a small group of patients.

The system is used to monitor blood flow velocity and pulsatility index in femoro-distal grafts for periods of up to 72 h postoperatively. The purpose-built Doppler probe is attached to the patient in the theatre or ward, and system programmed to collect data and display it as a trend graph at the bedside.

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HARDWARE

The basic functional block diagram of the computerised graft monitoring system is shown in Figure 1. The system comprises an IBM-compatible computer, a floating point digital signal processor (DSP) board* and a purpose built CW Doppler board. The related software implementations can also be considered as an integral part of the system.

The IBM-PC compatible computer was based on a 66 MHz 80486 chip. However, this is not an essential requirement. Minimum requirements are a 4 Mbyte system memory, a 40 Mbyte hard-disk, MS-DOS version 5.0 or later and a colour VGA monitor.

The DSP board is based on the AT&T WE™ DSP32C Digital Signal Processor, which is a 32-bit floating point processor designed for real time processing, interfacing to analogue I/O and other external devices, and efficient execution of typical DSP operations. The DSP32C provides an overall dynamic range in excess of 1500 dB, 1536 × 32 bit on chip memory and an 80 ns instruction time. The board also contains two 16 bit A/D, two 16 bit D/A converters and external memory.

The purpose built CW Doppler board is based on the quadrature detection method and the outputs are not separated. The block diagram of the board is illustrated in Figure 2. The directional channel separation is performed digitally in the DSP section[9,10]. The board is interfaced to the PC via a 'PC interface unit' and installed in one of the PC's expansion slots.

The unit can be divided into five main blocks: transducer, oscillator, transmitter, demodulator, and PC interface. The transducer was specially constructed from two identical pieces of piezoelectric material (PZT) as described by Dahnoun et al[4]. The oscillator is formed by using a crystal controlled integrated circuit. It generates a sine wave which minimizes the possibility of modulation with the signal harmonics radiated by the other switching circuits within the computer. The quadrature carrier signal is generated using a phase-shift circuit, which is basically a combination of low-pass and high-pass filters. The transmitter uses two transistors to form a transformer coupled push-pull class B amplifier which provides a low quiescent current and high efficiency at full output. The demodulator consists

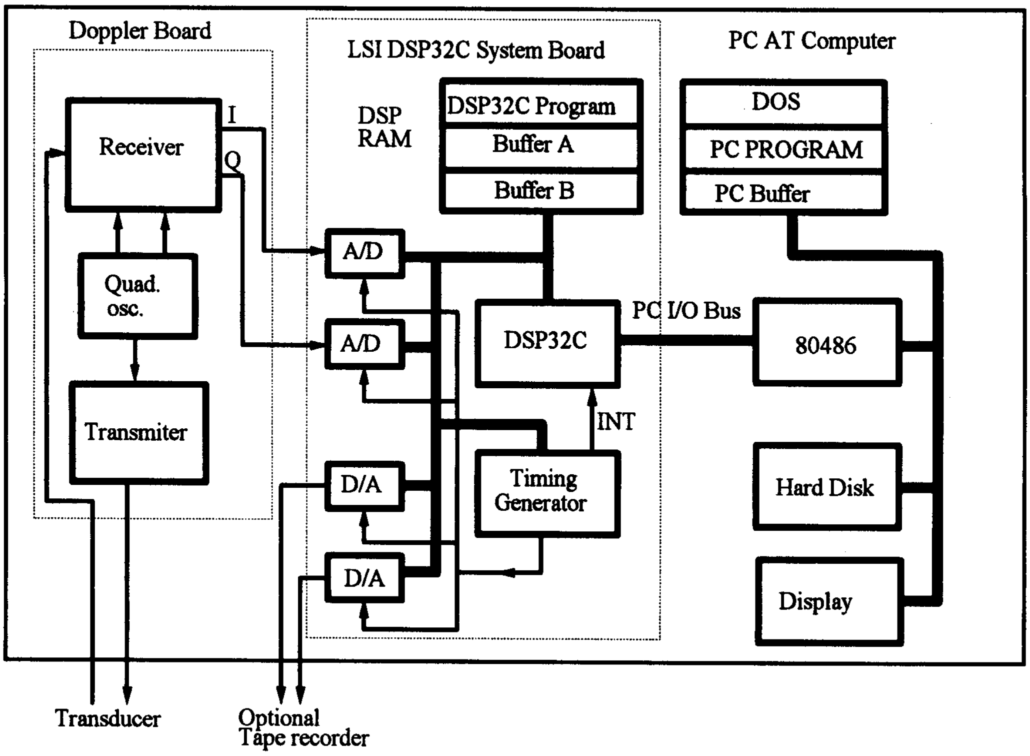

Fig. 1 Functional block diagram of the graft monitoring system.

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*Loughborough Sound Images Ltd, The Technology Centre, Epinal Way, Loughborough, Leics LE11 0QE, UK.

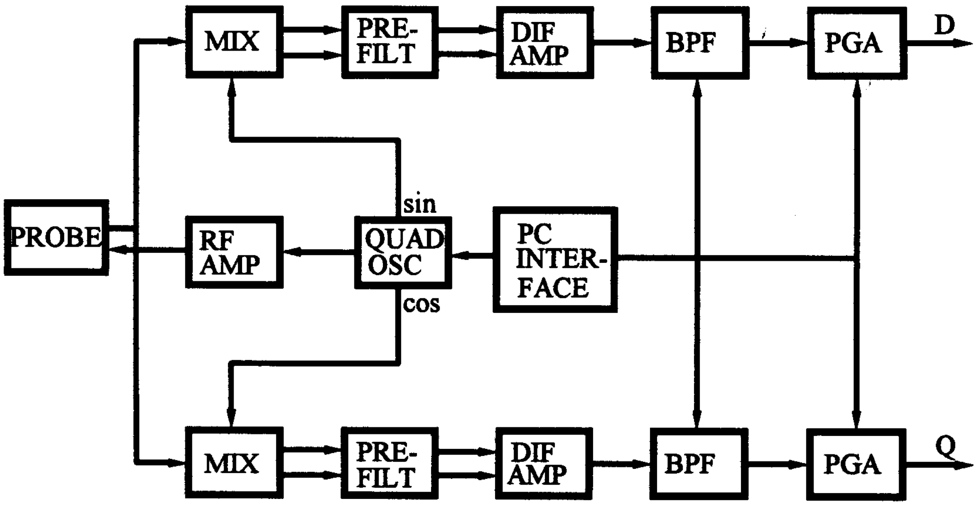

Fig. 2 Block diagram of the Doppler unit. MIX: mixer; DIF AMP: differential amplifier; BPF: band-pass filter; PGA: programmable gain amplifier.

of two mixers, differential audio amplifiers, programmable filters, and programmable gain amplifiers. The mixer circuit is based on the MC1496 balanced modulator-demodulator chip, which is sensitive enough to detect reflected ultrasound signals without a preamplifier, and exhibits a 70 dB dynamic range. The differential outputs of the mixers are converted to single ended outputs by differential audio amplifiers. This also provides rejection of the common mode noise. The band-pass filter is formed by a high-pass (wall thump rejection) filter (fixed cut-off frequency) and a low-pass filter (programmable cut-off frequency). Programmable gain amplifiers are also provided to adjust system gain through the keyboard. The overall system frequency response is shown in Figure 3(A and B). The PC interface provides communication between the computer and the Doppler board. The low-pass filter cut-off frequency and amplifier gain can be controlled by the software running on the computer via this interface. It also switches the Doppler board on or off when the system operates as an intermittent graft monitor.

The measured Dynamic range of the Doppler unit was about 50 dB; the cross-talk rejection approximately −30 dB throughout the usable frequency range.

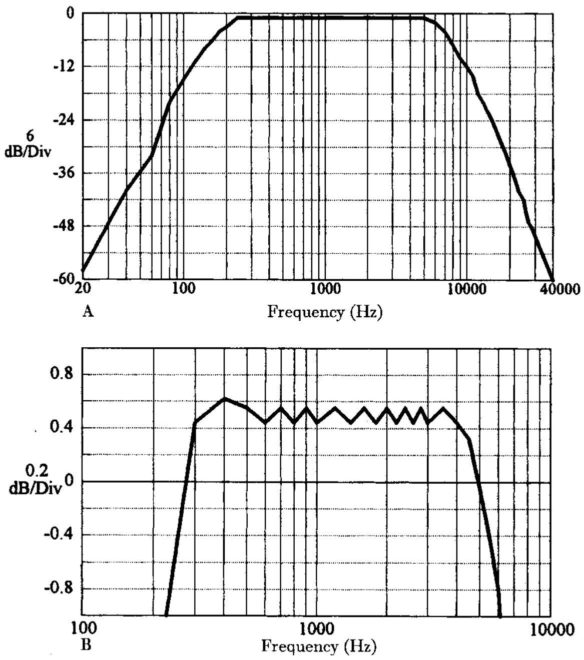

Fig. 3 (A) Frequency response of the Doppler system including the wall-thump filter (high-pass filter) and the low-pass filter. (B) Pass-band characteristic of the system. Note both vertical and horizontal scales for the two graphs are different.

SOFTWARE

The software organization, which is summarized in Figure 4, can be divided into three main parts: processing software, control software and analysis software.

The processing software is the program running on the DSP board. This runs independently and is responsible for: acquisition of the quadrature data digitized by the on-board ADCs; separation of flow direction; execution of the complex FFT and finding

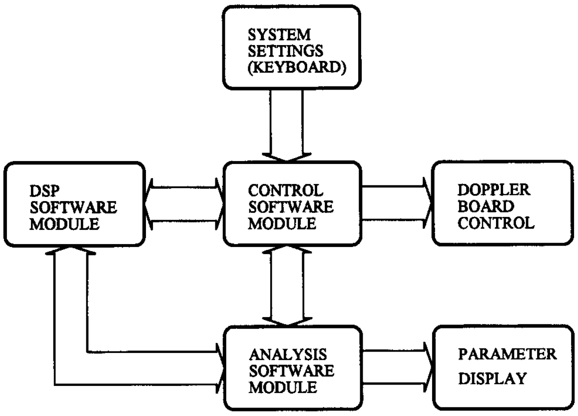

Fig. 4 The general software organization for the graft monitoring system.

the maximum and intensity weighted mean frequency bins in real-time. This software was written in the DSP32C assembler language. For the frequency domain display the complex FFT method[9] was used. The in-phase and the quadrature-phase Doppler signals were considered as the complex input signal for the FFT. This produces a directional Doppler frequency spectrum. This result is rearranged and displayed as a colour-coded sonogram. For the directional time domain outputs the phasing filter technique[10] was used. This process is independent of the frequency domain separation. The separated Doppler signals are sent out via the DSP board's DAC outputs.

The control software is a menu driven program running on the host computer and written in the C language. It performs data handling between the DSP board and the PC, controls the Doppler board settings, and allows interaction between the monitoring system and the operator. The latter occurs by selecting related options from the menu. Some parameters related to the DSP software can also be set.

The analysis software is responsible for the processing performed off-line after the Doppler board is switched off. Although the majority of the analysis software runs on the PC, some tasks such as the complex FFT and extraction of the frequency envelopes are performed on the DSP board. This first processes the stored quadrature data to generate a Doppler sonogram while it acts as a co-processor to the PC. It then analyzes this sonogram, and calculates the desired parameters.

SYSTEM OPERATION

The basic program flow for the graft monitoring system is depicted in Figure 5A. Figure 5B shows

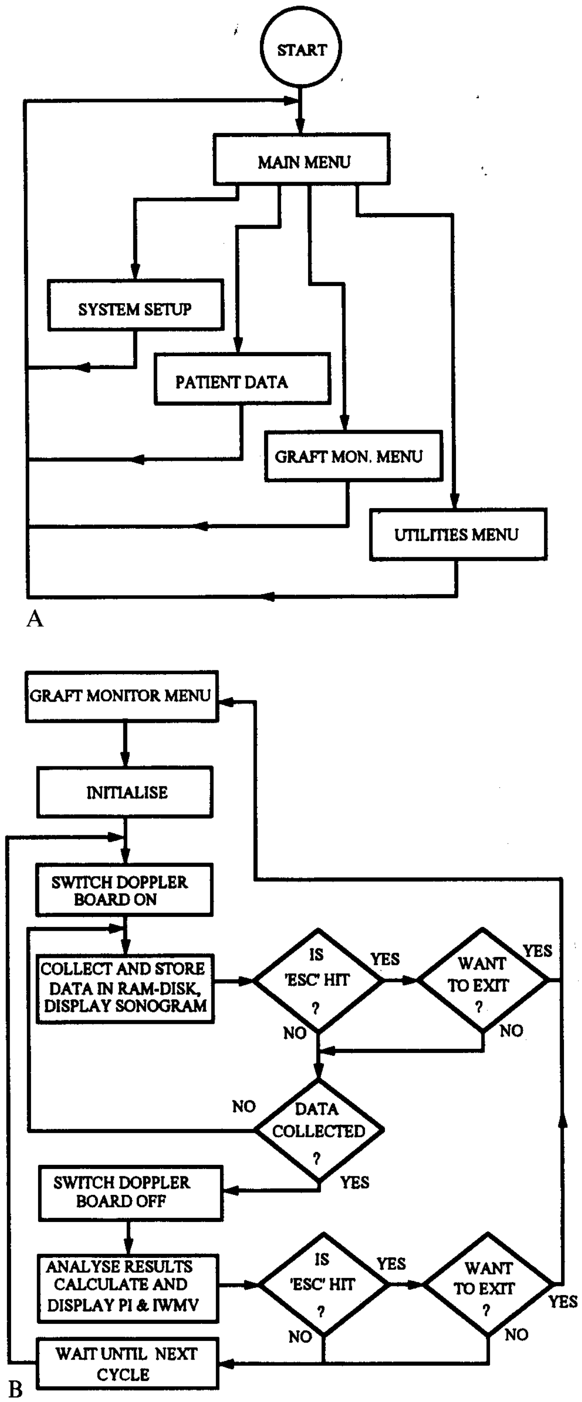

Fig. 5 (A) Basic flow diagram of the graft monitoring system software. (B) Flow diagram for the graft monitoring option.

the flow diagram for the graft monitoring option of the software. To operate the system in the monitoring mode the following sequence is followed:

1. The general area where the purpose built probe is to be attached, is covered with an 'op-site'

(Smith and Nephew Medical Ltd, Hull, UK) sterile, sticky, plastic dressing. This eliminates any possibility of infection. The best location within this area is determined by selecting the 'system setup' option from the main menu. This option provides a basic Doppler spectrum analysis function based on the FFT. After selecting the best signal by looking at the quality of the Doppler sonogram and listening to the audio Doppler signal, the probe is fixed at this position using a double sided-adhesive ring.

2. Patient data is entered by choosing the related option from the menu. Unless this option is chosen, parameters will not be stored.

3. The 'graft monitor' option is chosen and the intermittent monitoring parameters such as the Doppler board 'on-time', the FFT size, and the 'cycle-time' are initialized.

4. The monitoring sequence is begun. The system first switches the Doppler board on and displays the Doppler sonogram while it stores the quadrature data, whose length is determined by the 'on-time' setting, in ram-disk in real-time. Then the Doppler board is switched off, the signal processing is performed on the DSP board, the results are analyzed by the PC and plotted on the PC screen. The mean and maximum frequency envelopes and calculated parameters are stored in a file and the system waits for the next cycle. A typical graft monitoring display is shown in Figure 6.

The real-time process sequence of the monitoring software can be summarized as follows:

1. 256 complex data points are captured.
2. Time domain separation is performed by applying the phasing filter technique to the input data and the results are stored in an output array.
3. The input data are overlapped (50%) to obtain a 512 point complex array. A 512 point complex FFT, preceded by a complex Hanning windowing, is then applied.
4. The squared magnitude of the FFT output values are calculated, rearranged by shuffling the positive and negative frequencies, then scaled for the sonogram display. These results are stored in an output array.
5. The maximum frequency bin is determined by applying the modified threshold method[11] and the intensity weighted mean frequency is calculated.

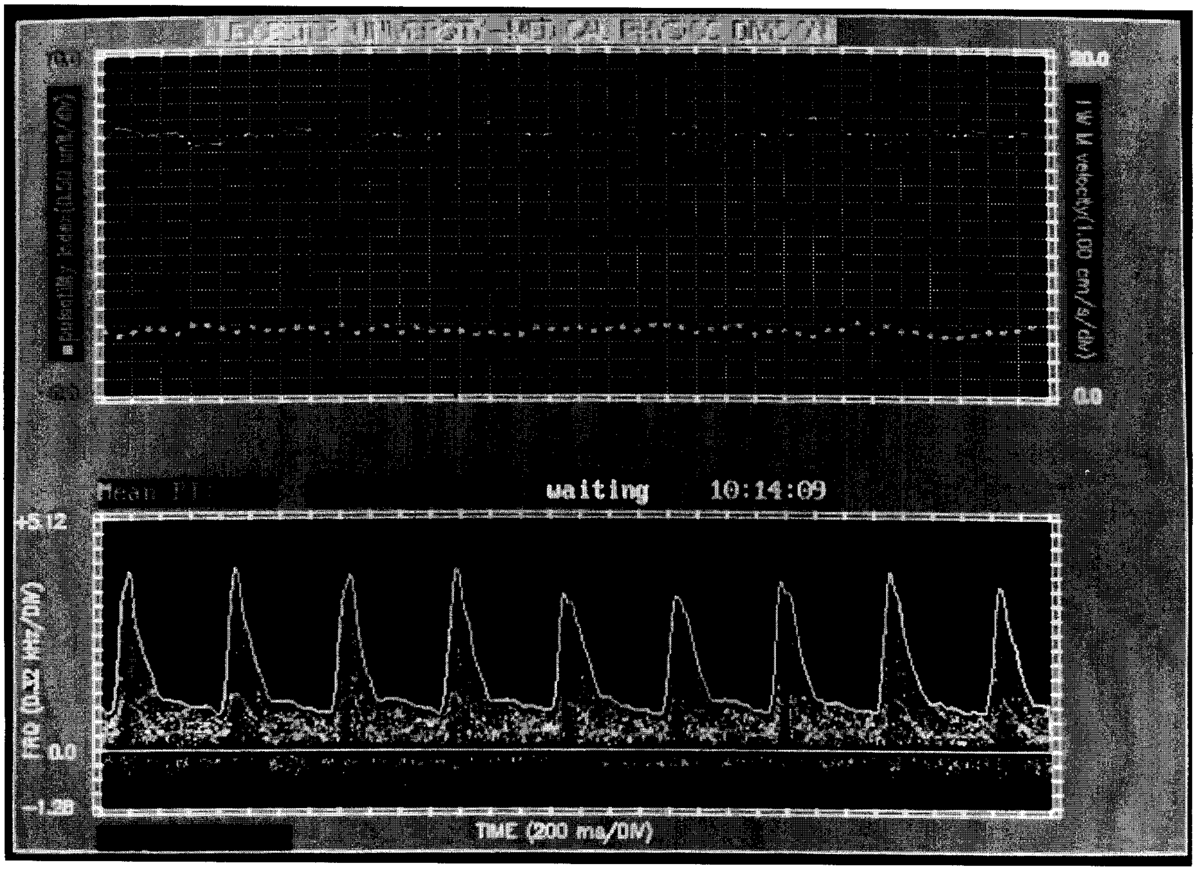

Fig. 6 A typical graft monitoring display.

Table 1 Summary of the processes performed by the DSP board and the PC

Processes performed in the DSP board	*Processes performed in the PC*
Capture of Doppler signals	Setting system parameters
Spectral analysis (Hanning windowing, complex FFT, etc)	Non-linear smoothing of the MFE and IWMFE
Extraction of the Maximum Frequency Envelope (MFE) and Intensity Weighted Mean Frequency Envelope (IWMFE)	Waveform identification
Time domain directional signal separation	Calculation of the indices
Output of directional signals	Control of the Doppler board
	Display of the results

6. The separated time domain signals are sent out via the on-board DAC. The spectrum analysis results and the frequency envelopes are read by the PC and at the same time a new complex data array is captured by the DSP board.
7. After performing all these processes in real-time they are repeated for the new data array.

Since the sampling frequency is 20.48 kHz all processes including capturing quadrature data, processing it for spectral analysis, time domain separation and displaying the results have to be completed within 12.4 ms. As the DSP32C has a pipelined processor architecture, the processes described above do not represent sequential execution. The major tasks such as outputting the separated Doppler signals and capturing the new quadrature Doppler signal are performed simultaneously. Table 1 summarizes the processes performed by the DSP board and the PC.

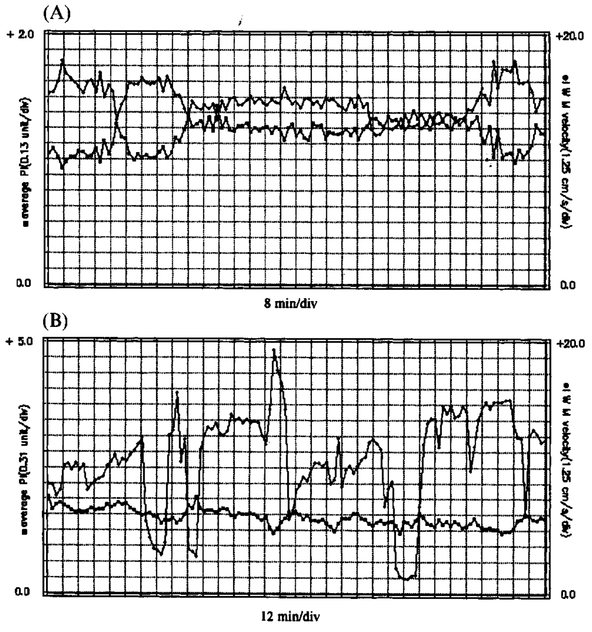

Fig. 7 Graph of the mean PI and the mean IWMV: (A) exhibiting a reciprocal pattern; (B) from a graft which became temporarily partially occluded.

CLINICAL STUDY

The system has been tested clinically by monitoring a number of patients. Two parameters, the mean pulsatility index (PI) and the mean Intensity Weighted Mean Velocity (IWMV), were calculated, monitored and stored on-line. Apart from the initial settings all these processes were performed automatically by the monitoring system, as explained above. Overall monitoring times and patient details for the first seven cases are summarized in Table 2.

Most of these grafts were monitored intermittently by using 3-min time intervals. The 'on-time' was 19.2 s for all studies. The maximum frequency envelope, mean frequency envelope, the mean PI, and the mean IWMV were stored on the hard-disk as binary files during the monitoring process. During the evaluation of the system, several practical problems were encountered, which were soon eliminated. Apart from the artefacts caused by patient movement, and some technical errors, the mean PI and the mean IWMV followed a reciprocal pattern. An example of this pattern, recorded during

Table 2 Patient details and overall monitoring times for each case

Patient no.	*Age*	*Operation*	*Graft*	*Result*	*Overal mon. time (h)*
1	64	FDB	ISVG	*	14.4
2	54	FDB	RVG (arm)	Failed	19.2
3	78	FDB	ISVG	Patent	19
4	76	FDB	ISVG + arm vein	Patent	34.1
5	75	FDB	ISVG	Patent	19.2
6	93	PDB	RVG	Patent	69
7	68	FDB	ISVG	Patent	64

*Proximal graft was patent, distal graft was occluded.
FDB: femoro-distal bypass; ISVG: In situ vein graft; RVG: reversed vein graft; PDP: popliteal-distal bypass.

one of the studies, is illustrated in Figure 7A. Figure 7B shows the graph of PI and IWM velocity recorded from a graft which was partially occluded as a result of the patient's position. Note the relatively high values of PI and low values of IWM velocity.

DISCUSSION AND CONCLUSION

The mean PI and the mean IWMV curves exhibited an opposite movement in almost all cases. As was noted in an earlier study[5] the PI increases while the IWMV decreases. Such a pattern indicates that the system is working and that the peripheral resistance is changing within fairly narrow limits. An unstable or random pattern suggests malfunction of the system. A very high pulsatility index and low velocity, or low pulsatility index and low velocity, may imply a failing graft (due to distal or proximal problems, respectively). However, the significance of various flow patterns will require further investigation, and should prove easier now that we are in a position to collect relatively large quantities of data.

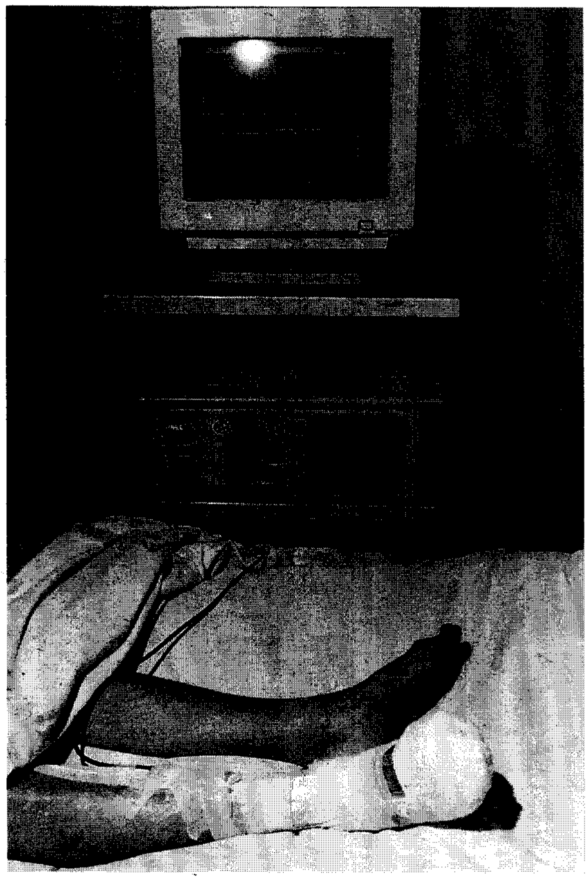

Fig. 8 The computerized graft monitoring system attached to a patient.

A number of practical difficulties have been encountered. The monitoring system has failed in some cases due to technical problems which had not been detected in the development stage or problems in management, such as misuse of the system by ward staff. One apparent technical failure was caused by the MS-DOS operating system caching utility 'smartdrive.exe' which was supposed to improve the performance of the computer. This utility interfered with the real-time quadrature signal recording when the calculated parameters were being written to the hard-disk during the program execution. This was solved by simply disabling this utility. The problems in management include unfamiliarity of staff with the system, patient resistance to continued monitoring, misplacement of the probe and unsuitable grafts (deep grafts).

Despite these difficulties, the system, which is shown in Figure 8 attached to a patient, has been used to monitor a number of grafts successfully. The system is now technically reliable but will need further clinical evaluation before its utility for monitoring various interventions and predicting graft failure can be determined.

Acknowledgement

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