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# A System for Analysis of Arterial Blood Pressure Waveforms in Humans

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Recent developments in arterial hemodynamics have indicated that the human arterial pressure waveform contains more information than is available from conventional sphygmomanometry. This information includes indices describing left ventricular systolic function and arterial properties. A cheap and reliable system was designed and implemented using readily available hardware for recording, analysis, and storage of arterial pressure waveforms. The system embodies an online technique for synthesizing ascending aortic pressure waveform from recordings made at different peripheral sites of the human arterial system. Eighteen indices are then derived from arterial pressure waveforms. This system can be used in an outpatient clinic for assisting in current pharmacological management of cardiovascular disease. It can also be extended to the critical care area, where the extra information provided aid in assessing the patient's condition. 

## INTRODUCTION

The sphygmomanometer provides only two features of the complex arterial pressure wave contour: the peak systolic and diastolic pressures. These values are routinely used in diagnosis and treatment of hypertension. However, there are other features of the arterial pressure wave contour which are of interest to the clinician. Analysis of arterial pressure waveforms can provide extra information about left ventricular function through assessment of heart rate, systolic time intervals, and myocardial oxygen supply and demand (*1*, *2*). Furthermore, the entire arterial pressure waveform is required for studying of arterial function. The peripheral resistance (*3*, *4*), arterial compliance (*5*), and wave reflection (*6–8*) are indices available only by analysis of arterial pressure waveforms (*9*, *10*).

Estimation of these indices of ventricular and arterial function require that measurements should be done closer to the heart, in the ascending aorta. Due to practical and ethical reasons, however, the arterial pressure waveforms are rarely recorded in the ascending aorta but in a peripheral artery. Since the arterial pressure wave contour is site dependent, due to wave propagation/reflection



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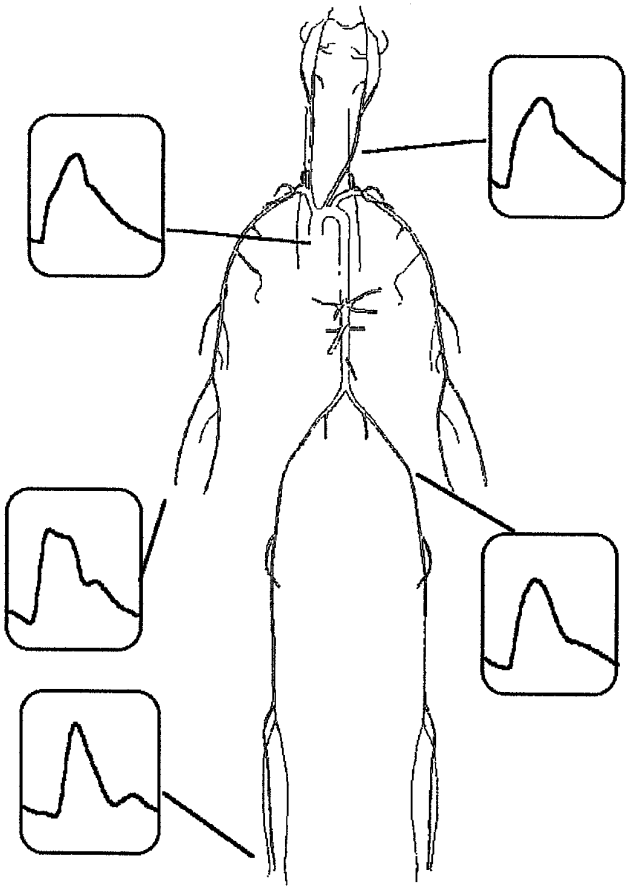

FIG. 1. The human arterial system and arterial pressure waveforms that are recorded in different sites in the body. Note that the peripheral waveforms are not only delayed with respect to the ascending aortic but also their contours are different.

phenomenon, the use of peripheral arterial wave contour for diagnostic purposes is limited (Fig. 1). This phenomenon, which could be described by transfer functions, delays and amplifies the propagating central aortic pressure wave contour. Recently, the transfer function in the upper limb was shown to be relatively consistent under a wide variety of conditions (*11*). Using this feature of the upper limb arterial system, the central aortic pressure waveform from peripheral upper limb pressure recordings was successfully synthesized. This novel technique, therefore, makes it possible to determine ventricular and arterial function from peripheral measurements.

This last technique and other feature extraction techniques have been previously described (5–7, 11). Unfortunately, however, these techniques have found

little clinical application as they were either scattered over various publications or their implemented versions, the computer programs, were not in the public domain.

This study brings together all these techniques in a single computer program which enables automated analysis of the pressure waveform in the clinical environment. It integrates current blood pressure waveform registration, central aortic pressure waveform synthesis, feature extraction techniques, and a database management system around affordable hardware. The overall system comprises a PC compatible computer, an analog to digital board to convert signals from various pressures and triggering sources, and software to gather, analyze, and report the pressure waveforms. Since it is of vital importance to run in near real-time in the clinical environment, provisions are also made to accelerate the entire process while minimizing costs. Information on the installation, operation, and maintenance of the system can be found in the user's manual of the system (see below for downloading details).

## METHODS

The basis of the system is the acquisition of pulses from a peripheral site (radial, carotid, femoral, brachial, axillary, subclavian, and dorsalis pedis arteries) or from the ascending aorta by means of a pressure registration technique such as applanation tonometry, photoplethsmography, or invasive catheterization. From these peripheral pressure waveforms, ascending aortic pressure waveforms are synthesized using various transfer functions. Indices such as pulse wave velocities and intensity and timing of pressure wave reflection can also be calculated to quantify the effects of different drugs or maneuvers on the arterial vasculature. It also contains a custom database management system to store pressure recordings. To achieve all these goals, the system software includes routines for signal acquisition, signal conditioning, feature extraction, parameter calculation, database maintenance, and report generation.

### *Feature Extraction and Analysis*

Wiggers described 14 different features present in the arterial pulse contour (*12*). However, recent studies have indicated that meaningful information can be obtained from a much smaller subset. These features consist of five time relative points on the arterial pressure wave contour: the wave foot, first shoulder, second shoulder, incisura, and duration of the pulse (Fig. 2). The wave foot and first shoulder coincides with the onset of left ventricular ejection and the peak flow, respectively. The second shoulder is considered to be associated with reflected pressure waves originating from the periphery and occurs later in systole. This shoulder is followed by the sharp incisura which coincides with the closure of the aortic valve and cessation of ventricular ejection.

Using these features, three distinct arterial pressure waveform types were classified (*6*). Type ''A'' pulses have a higher second shoulder than the first shoulder which augments the systolic pressure and is seen mostly in elderly

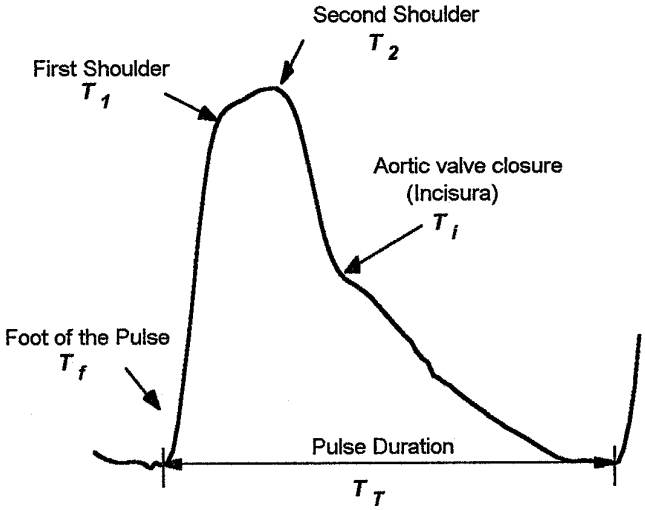


FIG. 2. The basic features of the arterial pulse. After the foot of the pulse indicating the onset of ejection determined from the trigger source, the pressure wave rises to an initial peak where it forms a shoulder. It then proceeds to a second shoulder which often constitutes the peak pressure in the elderly. The former point is related to timing of peak flow while the second shoulder to reflected waves. The end of ejection is associated with closure of the aortic valve which is often seen as a distinct incisura on the aortic pressure pulse.

patients. Type ''B'' or ''C'' pulses are seen in young patients where the second shoulder is equal to or less than the first shoulder, thus no systolic pressure augmentation is observed. Although these descriptions are categorical there is a continuous spectrum of pulses that can be observed due to different degrees of reflected waves present in the pressure waveform. The ''Augmentation Index'' provides such a measure for quantifying this late peak in the pressure pulse (*7*).

As these feature points could be described as inflection points along a curve, they can be identified using differentials of different orders (Fig. 3). For this purpose, particular importance is given to the determination of systolic onset (foot of the pulse), maximum of the first derivative (upstroke of the pulse), and systolic point (maximum of the pressure pulse). All other points can then be expressed in relation to these points according to the flow chart shown in Fig. 4. First, the peak systolic pressure, Tp, point is found by scanning the averaged pressure pulse for its maximum point. By locating a zero crossing from negative-to-positive that precedes the maximum point on the first derivative curve, Tmaxdpdt, a systolic onset point can be determined in the arterial pressure waveform. To determine the first shoulder corresponding to the peak flow, the third derivative's first zero crossing point from positive to negative after the Tmaxdpdt point is determined and labeled as Tzc3rd+−. The Tzc3rd−+ point is the point where the second shoulder is expected to occur in a ''young'' pulse (Type B or C) and could be determined as the first negative-to-positive zero

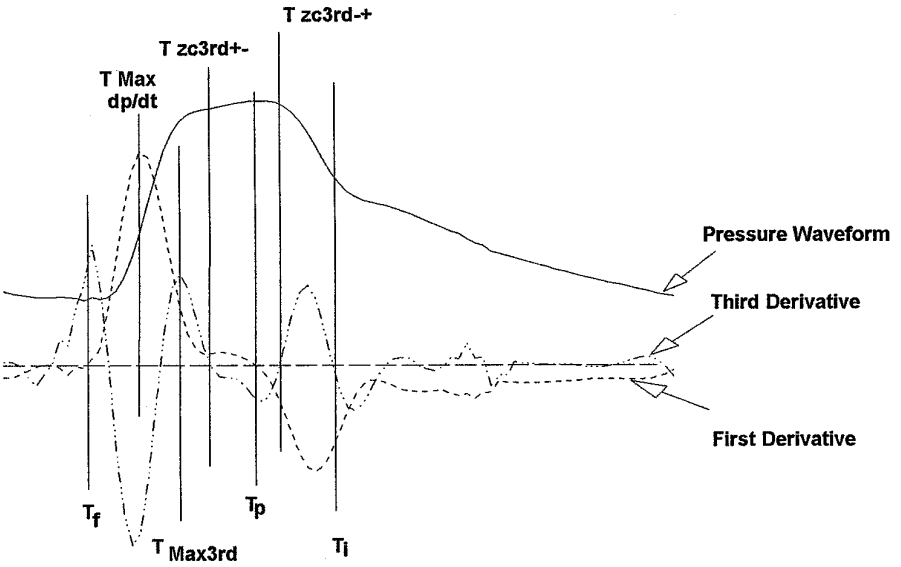


FIG. 3. A typical waveform (solid line) together with the first and third derivatives (dashed and dash dot line) used in extracting features (see text for more explanation).

crossing point after the Tp on the third derivative curve. The point of incisura representing the end of ejection can be determined once the second shoulder is found. It is considered to be at the first Tzc3rd+− point after the second shoulder.

Once these features are identified the following 18 values are calculated ($P[T]$ indicates the pressure at time $t$):

| | | |
|---|---|---|
| Ejection duration | $\mathrm{ED(msec)} = T_i - T_\mathrm{f}$ | [1] |
| Heart rate | $\mathrm{HR(beats/min)} = 60/T_\mathrm{T}$ | [2] |
| Pressure at first shoulder | $P_1\mathrm{(mm\ Hg)} = P[T_1]$ | [3] |
| Pressure at second shoulder | $P_2\mathrm{(mm\ Hg)} = P[T_2]$ | [4] |
| Pressure at diastole | $P_\mathrm{d}\mathrm{(mm\ Hg)} = P[T_\mathrm{f}]$ | [5] |
| Pressure at systole | $P_\mathrm{s}\mathrm{(mm\ Hg)} = P[T_\mathrm{p}]$ | [6] |
| Pressure at end-systole | $P_\mathrm{ES}\mathrm{(mm\ Hg)} = P[T_i]$ | [7] |
| Augmented pressure | $\mathrm{AP(mm\ Hg)} = P_2 - P_1$ | [8] |
| Mean diastolic pressure | $\mathrm{MDP(mm\ Hg)} = \dfrac{\sum_{i=T_\mathrm{i}}^{T_i} P_i}{T_\mathrm{T} - T_i}$ | [9] |

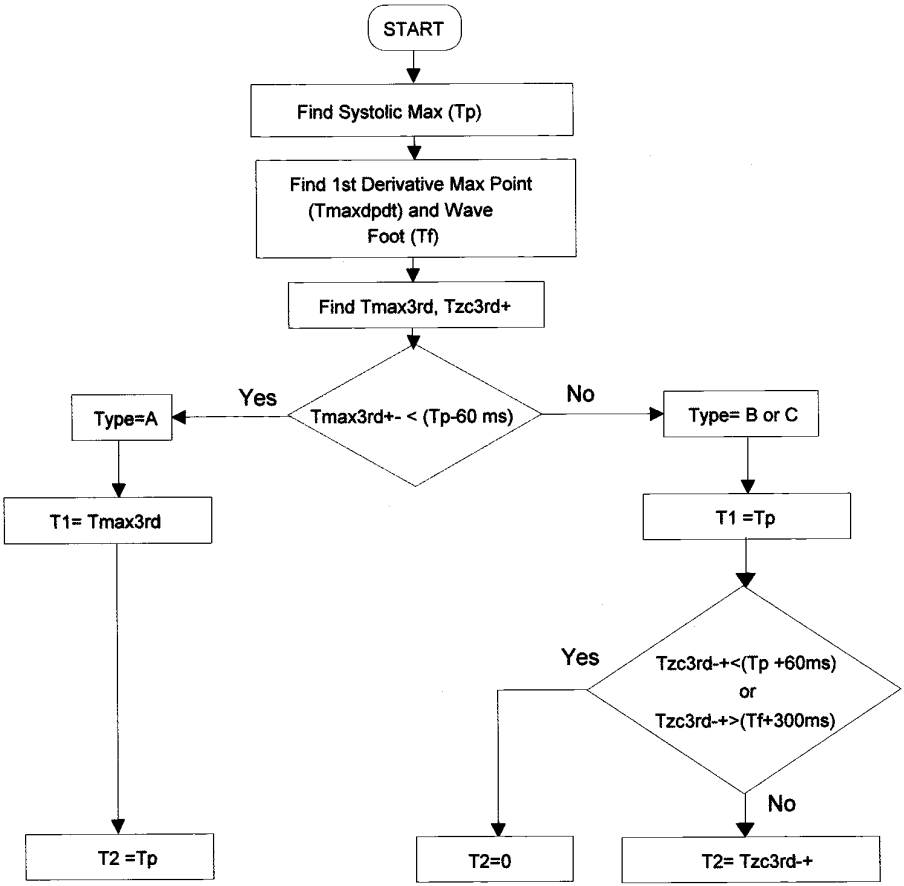


FIG. 4. The flow chart for extraction of time domain features in the arterial pressure waveform.

Mean arterial pressure
$$\mathrm{MAP(mm\ Hg)} = \frac{\sum_{i=T_f}^{T_T} P_i}{T_T} \quad [10]$$

Mean systolic pressure
$$\mathrm{MSP(mm\ Hg)} = \frac{\sum_{i=T_f}^{T_f} P_i}{T_i - T_f} \quad [11]$$

Augmentation index
$$\mathrm{AI(\%)} = 100 \times \frac{P_2 - P_d}{P_1 - Pd} \quad [12]$$

Tension time index
$$\mathrm{TTI(mm\ Hg \cdot beats/min)} = \mathrm{HR} \times \mathrm{MSP} \times (T_i - T_f) \quad [13]$$

Diastolic time index
$$\mathrm{TTI(mm\ Hg \cdot beats/min)} = \mathrm{HR} \times \mathrm{MDP} \times (T_T - T_i) \quad [14]$$

Subendocardial viability ratio $$\mathrm{SVI}(\%) = 100 \times \frac{\mathrm{DTI}}{\mathrm{TTI}} \quad [15]$$

Reflection transit time $$\mathrm{RT}(\mathrm{sec}) = T_2 - T_1 \quad [16]$$

Maximum rate of rise $$\mathrm{Max}\ dP/dt(\mathrm{mm\ Hg/sec}) = \mathrm{Max}\left(\frac{dP}{dt}\right) \quad [17]$$

Reference age $$\mathrm{RA\ (years)} = 0.642 \times (\mathrm{AI} - 100) + 33.81. \quad [18]$$

*Synthesis of the Central Aortic Waveform*

For recording sites between the ascending aorta and either carotid, radial, femoral, brachial, axillary, subclavian, or dorsalis pedis a transfer function is determined either by direct calculation from *in vivo* data (*11*) or from a mathematical model of the entire human arterial system (*13*). From each of these transfer functions, convolution windows representing the inverse transfer function are calculated (*14*) and stored as a look-up table.

The peripheral pulse is acquired at a rate of 128 Hz using an A/D and D/A converter (DT-2801, Data Translation, MA). This sampling rate is chosen since it not only facilitates operation of Fast Fourier transforms but also is well above the bandwidth of pressure signals. Also, it is low enough to reduce overhead in data storage and analysis.

At each sampling interrupt the arterial pressure waveform and, if present, a trigger waveform, Ts (usually an ECG waveform), are sampled from the A/D ports (Fig. 5). The arterial pressure waveform is then copied to a circular buffer of 10-sec length. If the trigger signal is not present, then arterial pressure waveform is also copied to a buffer of equal type and size for trigger information, otherwise trigger waveform will be copied into it. Online calculation of aortic pressure waveform is also performed during the acquisition step of the pulse. The arterial pressure waveform is directed to a convolution buffer, where it is convolved with the window to yield an ascending aortic waveform, Cs, which is subsequently stored into the same size circular buffer. An identical copy of ascending aortic waveform and arterial pressure waveform are dumped out from the D/A ports. The arterial pressure waveform is then displayed on the screen together with the derivative of the trigger waveform. The same process is repeated continuously until terminated by the user.

Upon the user's request data from all three buffers are transferred to the database records, excluding the last 2 sec to allow for data interruption which may occur during the initiation of the request. The contents of all buffers are smoothed using 7-point moving average filters to limit the bandwidth of the signals to 20 Hz. The data in the trigger waveform buffer is differentiated and further smoothed using first forward differentials and 3-point moving averages to find the triggering points and to eliminate the noise amplified during differentiation. Maximal and minimal thresholds are defined as the 60% of the maximum and minimum derivatives in the entire buffer content. This threshold value was

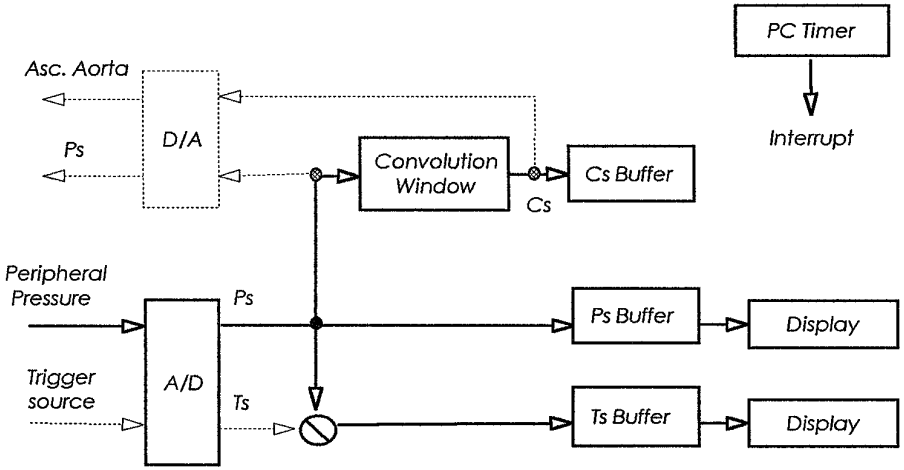


FIG. 5. Block diagram of the data acquisition section of the system. Peripheral pressure waveform and trigger source are fed into the respective buffers where they are kept and displayed. Peripheral pressure is convolved with the respective filter and stored as central pressure waveform. Depending on the presence of digital-to-analog converters the pressure signals (raw and convolved) are dumped out as analog signals. Entire events are synchronized with PC timer interrupts. Dotted lines indicate optional paths.

determined empirically using several pressure waveforms from various subjects. The positions of the onset of pulses are then determined by comparing them against the maximum threshold. The segments within these maximal and minimal thresholds are marked. The corresponding data from arterial pressure waveform and ascending aortic waveform are averaged to yield averaged recordings of peripheral and synthesized waveforms. These averaged waveforms are then subjected to the feature extraction processes and important parameters are calculated.

*Database Engine*

To allow access to the data for epidemiological and short term research, a database engine is installed as part of the software. Databases are indexed using AVL-trees (*15*) to keep the transaction time to a minimum. AVL-trees are derivations from the B-trees where it is ensured that a maximum of $\log_2 N$ searches would be sufficient to access a particular record ($N$ is the maximum number of elements in the tree). B-trees lack this insurance due to the unbalancing of the tree when sequential insertions are made. AVL trees however, take this into account by balancing the B-tree at each insertion and deletion so that there will be $\log_2 N$ levels present in a B-tree at all times. Using this algorithm, the software is able to locate a record from a list of 65,536 recordings in at most 16 attempts. Provisions are also made to ensure integrity and distribution of the

database across several platforms by obeying strict rules imposed by the system in accessing the database using indexes.

The data preserved in the database are the raw and averaged data for each peripheral and calculated central aortic waveforms as well as indices and values derived from them. A separate database is linked to the recording's database by the name of the patient and the time of visit. This second database keeps the information regarding the patient particulars such as age, sex, and anatomical and diagnostic data. A complete specification of the fields used in both databases are given in the program user's manual.

## RESULTS

A sample hardcopy of the system's output is given in Fig. 6. Following the details of the subject and recording details, a series of recorded waveforms (Fig. 6, top) and synthesized ascending aortic waveforms (Fig. 6, bottom) over 8 sec are given. The ensemble averaged recorded and synthesized waveforms are also given with flags identifying the first systolic and diastolic peaks. Similarly, the incisura has been identified and flagged. The times to these features from the foot of the waves are also given in milliseconds along the wave, together with the augmentation index. Maximum $dp/dt$ is given for the recorded waveform but not for the synthesized waveform. An index indicating the time to systolic onset would be displayed had a trigger signal (ECG or another pressure waveform) been acquired.

Shown below these waveforms are the indices derived from the analysis of central aortic pressures (Fig. 6). The extra pressure due to wave reflection is given as well as the indices of oxygen demand and supply. The subendocardial viability ratio index which indicates the subendocardial blood flow, is also given. This index is usually less than 70% under impaired blood flow conditions.

The system was recently used to analyze the interobserver variability of indices derived from tonometrically recorded pressure waveforms (*16*). Among many indices studied only the ED and max $dP/dt$ were found to be influenced by the operator. However, these variations were found to be small (ED, 1.6%; max $dP/dt$, 5.8%) and clinically acceptable.

## DISCUSSION

Sphygmomanometry and the information gained from that procedure has not changed appreciably since its introduction in 1905. Having the advantage of being noninvasive and inexpensive, it is used widely among clinicians. It is, however, limited. Since it does not provide the entire arterial pressure wave contour, extra information contained in the arterial pulse is not available to the clinician. As a result, the clinical applications of blood pressure waveform analysis have not been established. A coarse analogy to this phenomenon would be the recording of cardiac electrical activity with a galvanometer rather than with an electrocardiogram.

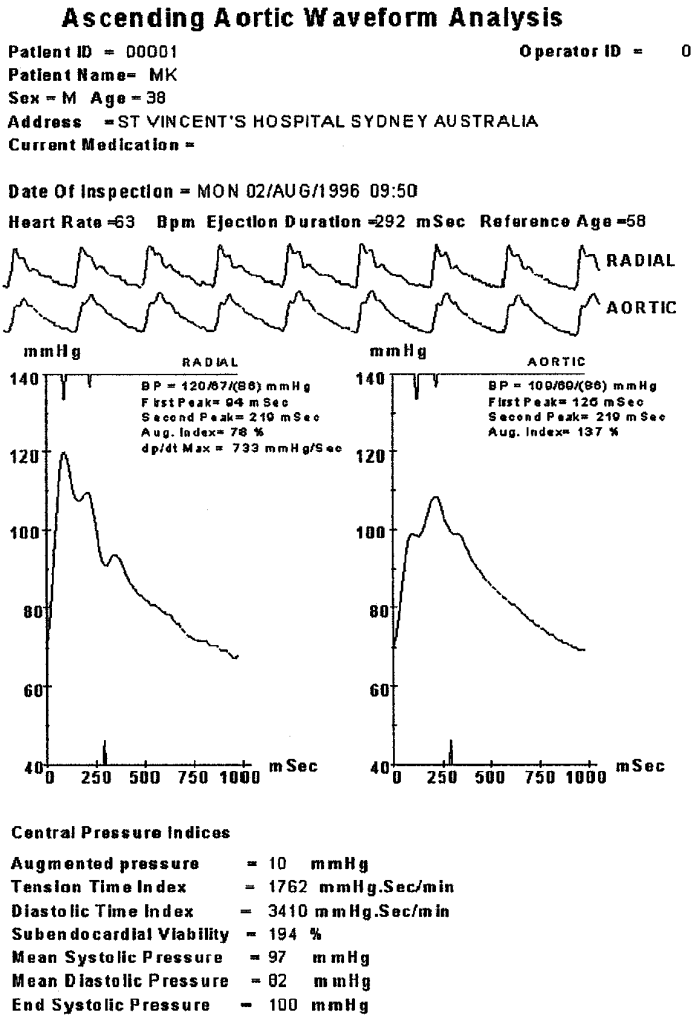


FIG. 6. A sample hardcopy report provided by the system.

The clinical significance of arterial pressure waveform has been noticed from ancient times. There were more than 100 different descriptions of the arterial pulse in ancient Greece. Traditional Chinese medicine still uses arterial pressure waveform analysis for detection and treatment of various ailments. However, these practices are qualitative. Instrumentation for recording the pressure waveforms was not utilized and importantly, guiding physiological principles were absent. As a result, modern medicine does not subscribe to them. Recently, however, the progress in arterial hemodynamics has begun to change this attitude. Several studies have been conducted analyzing the relationship between the arterial pressure waveform and gender, aging, vasoactive drugs, smoking, and diet.

Arterial pressure waveform analysis can also be used to quantify the stroke volume as pressure waveform is caused by the interaction of ventricular ejection and arterial impedance. Not surprisingly, since the beginning of this century several attempts had been made to achieve this goal with varying degrees of success (*17*). However, these methods required initial estimation of an index related to the arterial impedance such as peripheral resistance, pressure wave velocity or arterial compliance. Once this is done, usually through simultaneous aortic pressure and aortic flow measurements, the stroke volume could be estimated on a beat-to-beat basis. Unfortunately this system does not extract any of these impedance related indices and therefore, would not be useful to estimate stroke volumes from pressure waveforms.

This system may be inconvenient for some clinical practitioners who are not experienced with the intricacies of its setup. In its current form, the system requires the PC to be opened for installation and configuration of the data acquisition hardware. As the data acquisition board requires access to an industry standard expansion slot, notebook computers could not be used. Fortunately, recent developments in plug-and-play data acquisition hardware would eliminate both these limitations. Another possibility is the development of a stand alone custom unit dedicated to pulse waveform analysis. This would help a general practitioner to benefit from this system.

The program and its manuals can be downloaded from the internet WEB site: http://vmsuser.acsu.unsw.edu.au/~s8803219/dat.html.

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