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Determination of Systemic Blood Pressure via Autospectral Analysis of Oscillometric Data

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AN ABSTRACT OF THE THESIS OF Eugene Elie Warner for the Master of Science in Engineering presented 31 May 1984.

Title: Determination of Systemic Blood Pressure Via Autospectral Analysis of Oscillometric Data.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

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Graduate Office Representative

The currently accepted methods for measuring systemic blood pressure are either highly accurate but invasive in

nature or clinically convenient but prone to observer-related errors. A new oscillometric method uses sensitive signal conditioning and sensing equipment with a non-invasive arm cuff to record arterial pulsations. The goal of this study is to establish more reliable criteria for the identification of systolic and diastolic pressures from oscillometric data.

Arterial pulsations are gathered from human subjects with a hydraulic occlusive cuff and reduced by a spectrum analyzer that performs a forward Fourier transformation on the raw data. Oscillometric data were obtained at four cuff pressures: systolic and diastolic pressures, as determined by pre-test auscultatory measurements, an intermediate "range" pressure midway between the systolic and diastolic levels, and a suprasystolic pressure approximately 5 mm Hg above the systolic level. Data were gathered from several select subjects with air as the actuating cuff medium instead of water.

The test results showed that the cuff oscillations could be decomposed into a main pulse frequency and a set of harmonics at integral multiples of the pulse frequency. At suprasystolic levels an intermediate peak in the spectra, between the pulse frequency and the first harmonic correlated strongly with the auscultatory measurement of systolic pressure and was concluded to be a fairly reliable criterion for systolic pressure. No such criterion could be established for the diastolic pressure.

A comparison of the hydraulically and pneumatically gathered spectra revealed that the use of air as the actuating cuff medium led to an attenuation of the signal energy and the component frequencies of the oscillometric data. The amount of the frequency attenuation was pronounced at frequencies greater than 10 Hz and the difference in the signal amplitude between the hydraulic and pneumatic oscillometric data was approximately an entire order of magnitude.

DETERMINATION OF SYSTEMIC BLOOD PRESSURE

VIA

AUTOSPECTRAL ANALYSIS OF OSCILLOMETRIC DATA

by

Eugene Elie Warner

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE
in
ENGINEERING

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1984

TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

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INTRODUCTION

The American Heart Association estimates that almost 43 million Americans suffer from one or more forms of cardiovascular disease (CVD) and that in 1981 almost one million people died from CVD. This is twice the number of fatalities caused by malignancies and over nine times the deaths due to accident, the number two and three leading causes of death, respectively (1). High blood pressure, also known as hypertension, is the most prevalent form of CVD, afflicting over 37 million Americans and plays an important role in the mechanics of stroke and coronary disease.

The onset of hypertension is often the first sign that more serious cardiovascular problems are in the offing. Hypertension in itself is asymptomatic and must be tested for on a regular basis (2). Blood pressure can be measured in several ways with varying levels of accuracy and precision. The ideal measurement technique would be quick, inexpensive, convenient, and produce measurements with great accuracy and precision. The widely-accepted auscultatory method is excellent with respect to the first three requirements but does not measure blood pressure parameters with a very high degree of precision or accuracy (3).

The objective of this study is to (1) use a hydraulic variation of the oscillometric method to minimize energy and frequency attenuation of the signal, (2) record the pressure record in an archival form, and (3) establish new criteria for the determination of systolic and diastolic pressures. Because of the prevalence and silent nature of hypertension there is sufficient motivation to develop measurement systems and methodology that are more reliable and accurate, but as convenient as, present clinical techniques.

What follows is a brief introduction to elementary vascular physiology and nomenclature, followed by an examination of the three most common blood pressure measuring techniques. Special attention is given to the history and underlying principles of the oscillometric method. The design and implementation of a digital data acquisition and reduction system is discussed. Finally, an evaluation of the system based on results obtained from the reduction of data acquired from human volunteers is presented.

ELEMENTARY VASCULAR PHYSIOLOGY

The primary function of the systemic circulation is to deliver oxygen and nutrients to all parts of the body and transport wastes to the kidneys and carbon dioxide to the lungs for excretion.

The circulatory system is composed of six parts: the heart, arteries, arterioles, capillaries, venules, and veins. The heart is a four-chambered organ which pumps blood through the lungs and to the peripheral parts of the body. The right atrium receives spent blood from the vena cava and passes it to the right ventricle. When the right ventricle contracts it forces blood into the lungs via the pulmonary artery. After the blood has been oxygenated it returns to the left atrium of the heart via the pulmonary vein. From the left atrium the blood enters the left ventricle and, upon contraction, propels the blood into the aorta.

The aorta is the largest artery of the body. Arteries have very strong elastic walls and the blood flows under high pressure at velocities of up to 33 cm/sec (4). The aorta branches into peripheral arteries and the arteries branch into smaller arterioles. Arterioles are quite muscular and can relax or contract in response to central nervous system activity, thereby altering the blood flow to the capillaries. The capillaries are very thin, permeable vessels and this is where the blood exchanges oxygen for carbon dioxide and nutrients for waste.

After blood cells move through the capillaries they enter the venules which gradually meet and coalesce into veins. Veins are thin-walled but muscular vessels which can distend or contract, greatly altering their capacity. All veins feed into the ascending or descending vena cava and from there the blood returns to the heart.

The vascular system can be viewed as a closed, pressurized piping system. The arterial side of the system operates under relatively high pressures; the heart pressure varies from 80 to 120 mm Hg while the mean pressure of the aorta is approximately 100 mm Hg (4). The pressure gradually decreases as one measures pressure in distal arteries and is approximately 10 mm Hg when it exits the capillaries.

The venous side of the system acts as a blood reservoir for the body. About 79% of the entire blood volume is stored in the veins at a pressure of 10 mm Hg or less (4).

The heart is a cyclic, pulsatile pump. During each contraction the blood from the left ventricle is forced through the semi-lunar valves into the aorta. The blood already present in the system possesses a certain amount of inertia. Consequently, some of the pulse energy goes into distorting the aortic wall. When the semi-lunar valves open the pulse pressure wave begins traveling down the aorta to the peripheral arteries resulting in the well-known "pulse" phenomenon often felt in the radial artery at the wrist. The peak pressure during the contractive phase of the cardiac cycle is called the systolic pressure. The lowest pressure during the cardiac cycle is the basal, or diastolic pressure.

The diastolic and systolic values provide an indication as to how hard the heart is working and the compliance of the systemic arteries. A person is classified as hypertensive if the systolic pressure consistently exceeds 140 mm Hg and the diastolic pressure is consistently above 95 mm Hg. Systolic and diastolic values are commonly expressed as a non-simplified ratio of systolic to diastolic pressure, e.g. normal blood pressure is written as 120/80.

COMMON MEASUREMENT TECHNIQUES

There are several methods of obtaining estimates of systolic and diastolic pressures, each with their own advantages and disadvantages. The three most common methods are discussed below.

Direct (Intra-Arterial) Method

The most direct method to obtain systolic and diastolic values is to connect a calibrated pressure transducer in parallel with the circulatory system. The function of the transducer is to convert pressure energy into a proportional electrical voltage either through a change of resistance in a signal-conditioning circuit or a change in capacitance due to a relative linear displacement of transducer components (5). A peripheral artery is cannulated and the transducer is connected in parallel with the circulatory system. The voltage signal from the transducer is conditioned and amplified to a level suitable for driving a display or recording device.

The advantages of the direct method are obvious; very precise and accurate measurements are obtained almost instantaneously and a permanent pressure vs. time history can be obtained. The main disadvantages are the cost of the support equipment and the invasive nature of the measurement making the direct method the measurement technique of choice in the surgical theater but impractical in a routine clinical setting.

Auscultatory Method

Auscultatory measurements of systolic and diastolic pressure are the most common ones outside of the operating room. The equipment consists of an inflatable pneumatic cuff, a sphygmomanometer calibrated in mm Hg, and a standard stethoscope.

To obtain an auscultatory measurement the properly sized pneumatic cuff is wrapped around the upper arm with the lower edge approximately one inch above the bend of the elbow of a quiescent patient. The proper cuff size is crucial; a cuff that is too narrow will produce erroneously high readings while a cuff that is too wide will produce spurious low readings. The circumference of the upper arm determines which cuff size should be used (3). The radial artery is then palpated as the cuff is inflated to give a rough estimate of systolic pressure. The observer places the bell head of the stethoscope in the antecubital space, over the brachial artery, and inflates the cuff to approximately 30 mm Hg above the estimated systolic pressure. The observer then deflates the cuff at a rate not to exceed 2-3 mm Hg/sec while listening for certain arterial sounds through the stethoscope. As the pressure decreases and the lumen of the artery opens the sound of blood flow undergoes qualitative changes. These Korotkov sounds, named so after the Russian physician who first described them, have been delineated into five phases which aid the observer in determining systolic and diastolic pressure. Systolic pressure is taken to be the manometer reading at which "faint, clear tapping sounds" (phase I Korotkov sounds) are detected. Diastolic pressure in adults is taken as the pressure at which all arterial sounds disappear (phase V Korotkov sounds).

The wide clinical acceptance of the auscultatory method is due to the fact that fairly accurate measurements of systolic and diastolic pressures can be obtained non-invasively with relatively inexpensive equipment. The main drawback of the auscultatory method is the opportunity for measurement error. Biological variations may also introduce error and can be attributed to a myriad of factors including emotional state, ambient temperature, season, presence of systemic stimulants, recent physical activity and postural position, to name a few. These biological variations are independent of the measurement technique and in general cannot be controlled. The best that can be done is to be aware of the factors affecting blood pressure and record them if they are considered significant.

Measurement errors are easily committed by an observer using the auscultatory method, in part because of the subjective process of detecting the key Korotkov sounds. A large source of error is the recording and reading errors that plague even the most careful of observers. Such errors may be in the form of digit preference when reading data, digit transposition when recording pressure values, parallax error in viewing the manometer, and simple misreading of the manometer. Other errors not directly associated with data collection are any sensory impairment, measurement in a noisy environment that makes identification of key Korotkov sounds impossible, or subconscious bias on the part of the observer.

The Oscillometric Method

The third method of determining systolic and diastolic pressure combines elements of the direct and auscultatory methods. The measurement of pressure with the oscillometric method combines aspects of the auscultatory method with the sensitivity and objectivity of the direct technique.

To obtain oscillometric readings suprasystolic pressure is applied to the brachial or radial arteries by an outside agent, usually a pneumatic or hydraulic cuff. The cuff pressure is then lowered at the same rate as in the auscultatory technique (2-3 mm Hg/sec) while the observer records the arterial pulsations with instrumentation distal to the occlusion. When the cuff pressure is decreased to just below systolic pressure the arterial pressure pulse suddenly breaks through the occluded region and is recorded by the instrumentation. The pulsations are very pronounced until the diastolic level is reached whereupon the waveform undergoes a slight change and decrease in amplitude (4).

The oscillometric method, in its present form, suffers from many flaws in sophistication and methodology; while the technique outlined above will yield a reasonably accurate value for the systolic pressure the diastolic value is not nearly as certain because of the rather subtle changes in the waveform at diastolic pressure. Another disadvantage is that while there are many commercially available oscillometric units their use of pulse amplitude as the criteria for systemic pressure is of low reliability, in part because these units are pneumatically activated. The use of air to transmit the arterial pulsations to the transducer results in a loss of signal amplitude and fidelity with respect to the arterial pulse wave.

Despite the present drawbacks the underlying principle of the oscillometric method is fundamentally superior to the direct or auscultatory method with respect to convenience and potential accuracy of the measurement. The technique is non-invasive and can therefore be employed in a clinical setting in much the same manner as the auscultatory method, and the opportunity to make high fidelity recordings of the arterial pressure wave allows a more studied and objective reduction of the raw data to arrive at values for systolic and diastolic pressures.

HISTORICAL REVIEW OF THE OSCILLOMETRIC METHOD

A study of the oscillometric method was undertaken in 1901 by Howell and Brush. They observed a relation between the arterial pressure and the amplitude of the pressure reading when the artery was subjected to an external counterforce (6). The method did not gain clinical acceptance because the instrumentation at that time could not produce repeatable results.

A much later study by Geddes _et al_ of Purdue sought to quantify the relation between oscillation amplitude and arterial pressure with the aim of positively determining systolic and diastolic pressure. Using a small piezoelectric contact microphone and a standard (12 cm) pneumatic cuff the Korotkov sounds were picked up, bandpass filtered in the 30-300 Hz range, and superimposed on the recording of the cuff pressure. Data reduction was done by comparing the P vs. t records of the Korotkov sounds and the cuff pressure with auscultatory measurements of the systolic and diastolic points serving as a reference. As the cuff pressure was lowered the cuff oscillations gradually increased in amplitude, reaching their maximum approximately midway between the systolic and diastolic pressures. The cuff oscillations then decreased in amplitude as the cuff pressure fell below diastolic pressure. Geddes and his co-workers determined the systolic pressure to be the point on the record where the cuff pressure oscillations reached one half of their maximum value as the cuff was deflated and diastolic pressure was encountered when the cuff pressure dropped to 80% of the maximum amplitude. These relationships were found to overestimate human blood pressure values by as much as 10% and 8%, respectively, when the auscultatory method was used as a standard (7).

Geddes and his research team provided an excellent calibration for the oscillometric method when the auscultatory method was used as a reference; much of the subjective aspects were eliminated with the use of the contact microphone but the Korotkov sounds were still used to determine systolic and diastolic points.

Bhattarai and Chen of Portland State University, and Reynolds of the Oregon Health Sciences University, recognized the subjectivity inherent in the use of the Korotkov sounds as the criteria in blood pressure measurement. They hypothesized that parameters other than the amplitude of the cuff pressure oscillations could provide the criteria necessary to determine the diastolic and systolic points. A hydraulic occlusive cuff (HOC) was developed and operated in conjunction with a Harvard syringe pump and a Gould-Statham model PL-280 TC pressure transducer. A block diagram of their experimental set-up is shown in Fig. 1.

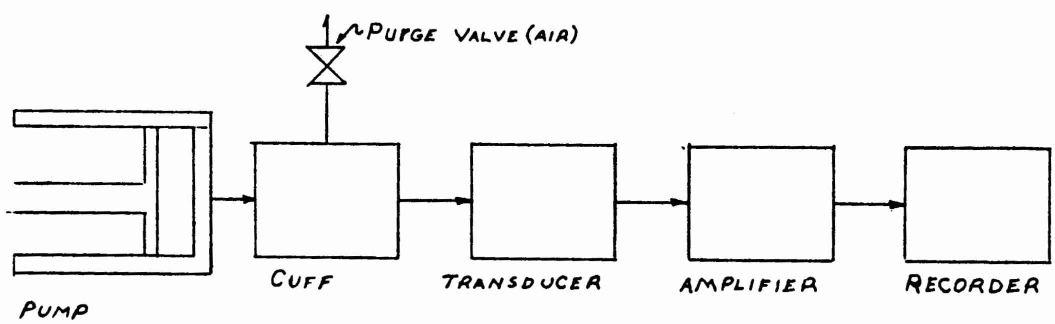

Figure 1. A block diagram of the experimental set-up used by Bhattarai, Chen, and Reynolds.

The system components were tested on 60 human subjects and the raw data were recorded as a P vs. t record on a strip-chart recorder. Auscultatory measurements made at the same time as the oscillometric record served as a reference. Data reduction consisted of careful visual inspection of the strip-chart record. When the cuff pressure rose to systolic level, as determined by the auscultatory measurements, the oscillometric waves underwent a pronounced flattening of the troughs. Further statistical analysis of the data revealed that this flattening occured within ± 10% of the diastolic and systolic points for upwards of 90% of the subjects (8).

Bhattarai, Chen, and Reynolds succeeded in finding a strong correlation between the shape of the cuff pressure oscillation and the auscultatory determination of systolic and diastolic pressure but the visual inspection of the time domain wave representation suffers from the same type of interpretive bias as the auscultatory method. For the oscillometric method to gain clinical credibility more work must be done on the data acquisition system and on the method to reduce the raw data.

THE DATA ACQUISITION SYSTEM

The purpose of the data acquisition system is to sense and store the incoming blood pressure pulse data in a faithful, permanent manner for subsequent retrieval and analysis.

The entire system can be naturally divided into two categories: sensing/signal conditioning and data storage.

SENSING AND SIGNAL CONDITIONING

The detection and measurement of arterial pulsations requires a mechanical apparatus to apply external pressure on an appropriate artery and an electromechanical sensing device to detect and signal the oscillations. The external pressure is generated by a syringe pump mechanism designed and built at Portland State University. A variable speed DC motor drives a 50:1 reduction lead screw which in turn inserts and extracts a plunger from the barrel of the plastic syringe. A two-way stopcock at the tip of the syringe directs the flow of water either to/from the reservoir or to/from the HOC. The HOC is the same one used by Bhattarai et al; it is essentially a Lucite cuff with a gum rubber bladder that is filled and emptied by the syringe pump. The cuff is also equipped with an air purge valve and an access port for the transducer.

A Gould-Statham P23-ID pressure transducer is used to sense the pressure oscillations in the cuff. The sensor, a diaphragm-type strain gage, forms one leg of a Wheatstone bridge signal conditioning circuit. The transducer signal is amplified by an Action Pak 4051 strain gage amplifier housed in the syringe pump case. The full-scale range of the P23-ID is 0-300 mm Hg. A block diagram of the sensing components and their arrangement is shown in Fig. 2.

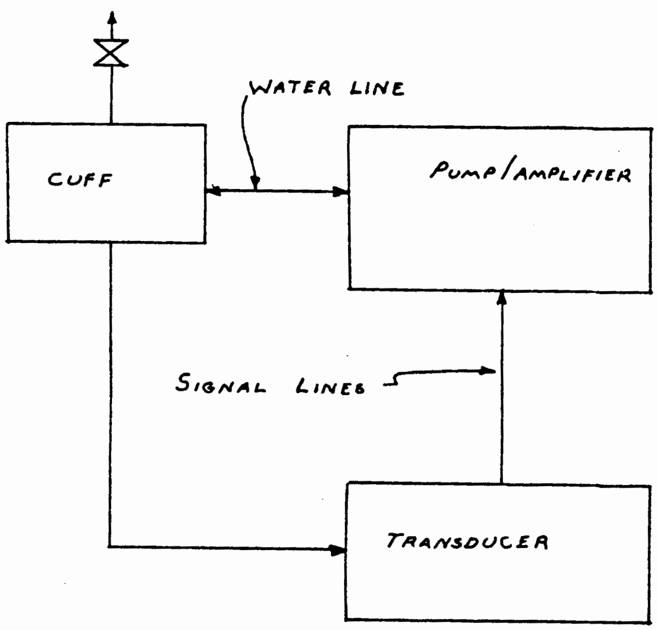

Figure 2. A block diagram of the HOC, transducer and pump/amplifier components.

DATA STORAGE

The function of the data storage system is to produce a high fidelity record of the arterial pulsations for future reduction to identify the systolic and diastolic values. The data can be stored in one of two forms, either as a continuous analog signal on magnetic open-reel tape or as a discrete digital representation on a 5¼" magnetic diskette commonly used for data storage on many personal computers.

The decision to incorporate a digital rather than continuous storage mode into the data acquisition system was primarily to take advantage of the relatively high noise immunity inherent in a digital system. If the data signal is of a sufficiently large amplitude with respect to the resolution of the analog-to-digital (A/D) convertor then much of the low-amplitude noise normally associated with the low-power motors and amplifiers is automatically filtered out by the A/D convertor. As the resolution of the convertor increases so does the resemblance of the digital record to a perfect analog record, i.e., a tape record minus the noise introduced by the tape or the recorder components.

The conversion and storage of the continuous signal is handled by three separate components: the A/D convertor, which actually converts the continuous voltage to a digital value, the real-time clock which determines the sampling rate, and the Apple II+ computer which controls the convertor and clock functions as well as providing the temporary storage space for the data and prompt messages to the user for further program inputs. Each of these components are described in more detail in the following subsections.

The A/D Convertor

The A/D convertor is the electronic circuitry necessary to arrive at a digital value proportional to the sampled voltage. The convertor used for this project was an Interactive Structures 12-bit, 16 channel successive approximation type convertor working over a 0-5 volt dynamic range. The successive approximation circuitry performs a twelve step binary search of the dynamic range and tests to determine whether the signal is present in the upper or lower half of the range tested, e.g., in the first step the convertor tests the upper 2.5 volts of the range; if the signal is greater than 2.5 volts the most significant bit (MSB) of the convertor register is set to a high state and if the signal is less than 2.5 volts the MSB is set low. The convertor then repeats the process on the next-MSB of the convertor register, dividing in half the 2.5 volt range in which the signal is determined to be and performing a similar binary search. This type of conversion system, when used with a 12-bit register, yields an absolute resolution of the signal of 1 part in 2^{12} or a relative resolution over a 5.0 volt range of 1.2 mV, i.e. a 1.2 mV change in the signal is required to produce an incremental change in the 12-bit convertor register.

The speed and accuracy of the successive approximation convertors are quite high; a complete 12-bit conversion is completed in 20 microseconds, giving an upper frequency bound to the sampling rate of the convertor of 50 KHz and a measurement uncertainty of ± 1.2 mV for each data point. There is a maximum of -95 dB crosstalk from unselected channels and an input impedance of 10 MegOhms.

Physically, the A/D convertor consists of an analog unit and a printed circuit logic board which resides in one of the input/output (I/O) expansion slots on the main logic board of the Apple II+ computer. The analog box contains a 5:1 and 10:1 operational amplifier for the conversion of low-voltage signals.

The Real-Time Clock

The use of the FFT algorithm for the data reduction scheme required that the data be sampled at evenly spaced time intervals, thus necessitating the use of a real-time clock to generate precise sampling intervals.

The Mountain Computer Inc. real-time clock operates at a frequency of 1 MHz ± 0.001% and can generate interrupt signals at frequencies from 100 microseconds to slightly over one year. An interrupt is a control signal from some peripheral device of a computer to the computer central processing unit (CPU). Upon reception of an interrupt signal the computer completes the instruction-in-progress and transfers program control to a pre-arranged program memory location. The program stored at this memory location and higher is often called an "interrupt handler" and it manipulates commands and/or data required by the interrupting peripheral device. After the interrupt-handling software completes execution, control is returned to the program that was interrupted.

The clock is similar in construction to the A/D convertor. It consists entirely of a printed circuit board and integrated circuits. The clock is installed in one of the I/O expansion slots located on the Apple II+ main logic board.

The Apple II+

The Apple II+ acts as a system controller for the entire data acquisition scheme. It provides 48K bytes of random access memory (RAM) which stores the control software and the digitized data before it is transferred to the more permanent magnetic disk storage.

Interfacing Considerations. The A/D convertor and the real-time clock are peripheral I/O devices *i.e.* they are not integrated with the rest of the Apple II+ hardware. These units were expressly designed for installation in one of the eight I/O slots located at the back of the Apple II+ logic board. These slots are memory-mapped from hexadecimal location $C080 to $C0FF and the CPU of the Apple II+ can communicate with any peripheral device installed in these slots by sending a transistor-transistor logic (TTL) control signal to the appropriate memory location (9).

Software

The essential component of this digital data acquisition system is the software. It determines the sampling rate, intermediate disposition of the raw data, and communicates to the user important information concerning the amount of machine memory used in compiling a data record.

The system components are controlled by the Apple II+ computer via a main BASIC program and three machine language subroutines. The BASIC driver (A/D) and the machine language programs (I-HANDL) are discussed in more detail in the following sub-sections.

BASIC Driver (A/D). The BASIC program informs the user when the A/D convertor and real-time clock are properly configured to collect data. The machine language program I-HANDL is a subroutine of this BASIC program. A CALL from A/D to the initialization subroutine of I-HANDL configures the clock interrupt vectors and status flags.

Upon return from this subroutine A/D prompts the user to begin data collection by pressing the carriage return on the keyboard. A/D then starts the clock and waits for an input from the keyboard that signals the end of the data collection session but while the BASIC program is waiting the real-time clock interrupts the Apple II+ CPU every 0.01 seconds to sample the transducer output by branching to the second subroutine of I-HANDL that controls the A/D convertor.

When data collection is finished the clock is turned off and a call is made to the final subroutine to re-enable certain interrupts and restore interrupt vectors to their original values. The program then displays the memory address of the last data point and the total length, in bytes, of the record. A flow chart of A/D is shown in Fig. 3.

Initialization Program. This subroutine specifies the machine memory segment where the storage of raw data begins, enables the clock interrupts, and stores the hexadecimal value $0326 in the interrupt entry vectors $03FE and $03FF; the value $0326 is the beginning memory location of the interrupt handling software. When an interrupt signal is received by the Apple II+ CPU the instruction-in-progress is completed. The program counter is then loaded with the 16-bit value of $03FE and $03FF and program execution is resumed from that memory address

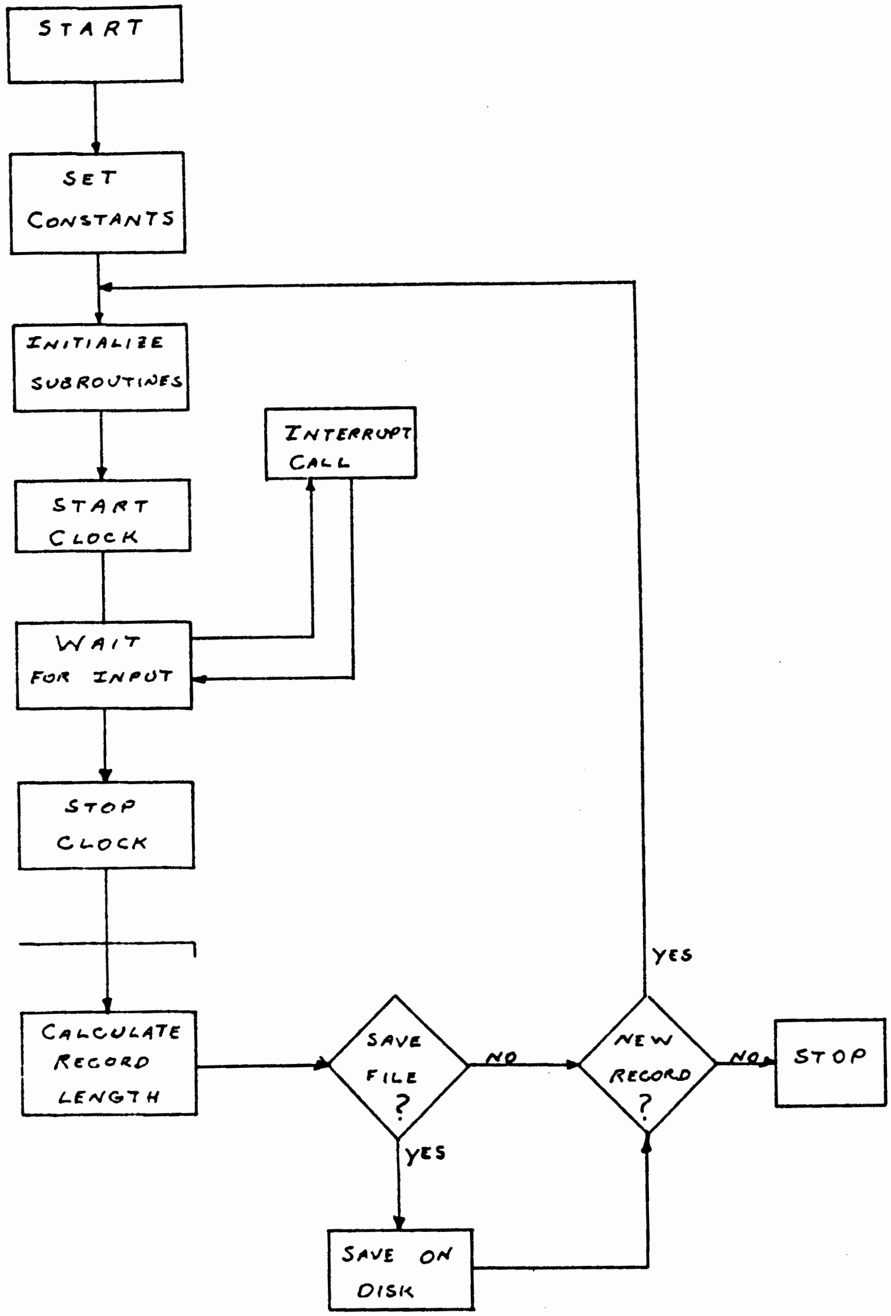

Figure 3. A flow chart for the BASIC driver program A/D. Dotted lines denote an interrupt call.

until a return-from-interrupt (RTI) instruction is encountered, whereupon program control is returned to the interrupted program at the next instruction after the instruction that was interrupted.

The Interrupt Handler. This is the subroutine which initiates conversion of the transducer signal, retrieves the results, and stores the data in machine memory.

The program first stores the processor registers on the computer stack so essential flags and status registers are not lost when processing the interrupts. The conversion is started and two buffers are prepared to receive the data. A series of No-OPeration instructions (NOPs) are executed as the Apple II+ waits the twenty microseconds required for conversion.

The A/D convertor stores the digitized value in a 12-bit register but since each internal memory location of the Apple II+ is eight bits in length the digitized data must be stored in two consecutive memory addresses, one containing the four most significant bits of the result and the other containing the remaining eight bits. Consequently, two memory locations and two data fetch operations are needed per data point.

Once conversion is complete the four most significant bits are fetched and stored. The buffers are then incremented and the remaining eight bits are fetched. The clock is reset for the next interrupt, and the registers previously saved are restored before returning to the main program.

Finish Program. This final subroutine is called from A/D after all data has been collected. It disables all clock interrupts and re-enables lower priority interrupts and restores the original value to the interrupt entry vector that was changed in the Initialization program.

Flow charts of the Initialization and Finish routines are given in Fig. 4. A flow chart of the interrupt handler is given in Fig. 5 and a listing of all programs written for the data acquisition system is presented in Appendix A.

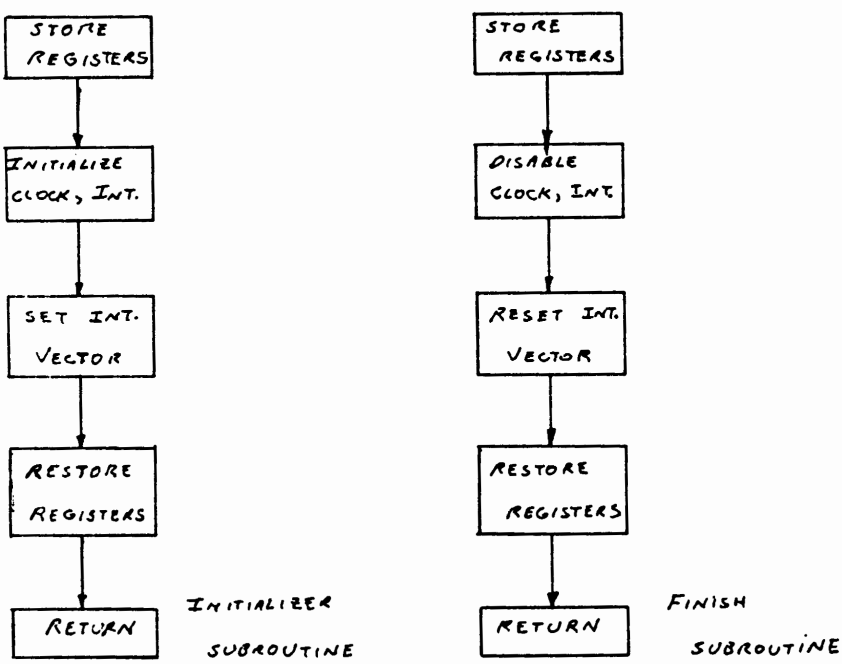

Figure 4. Flow charts detailing the Initialization and Finish machine language subroutines.

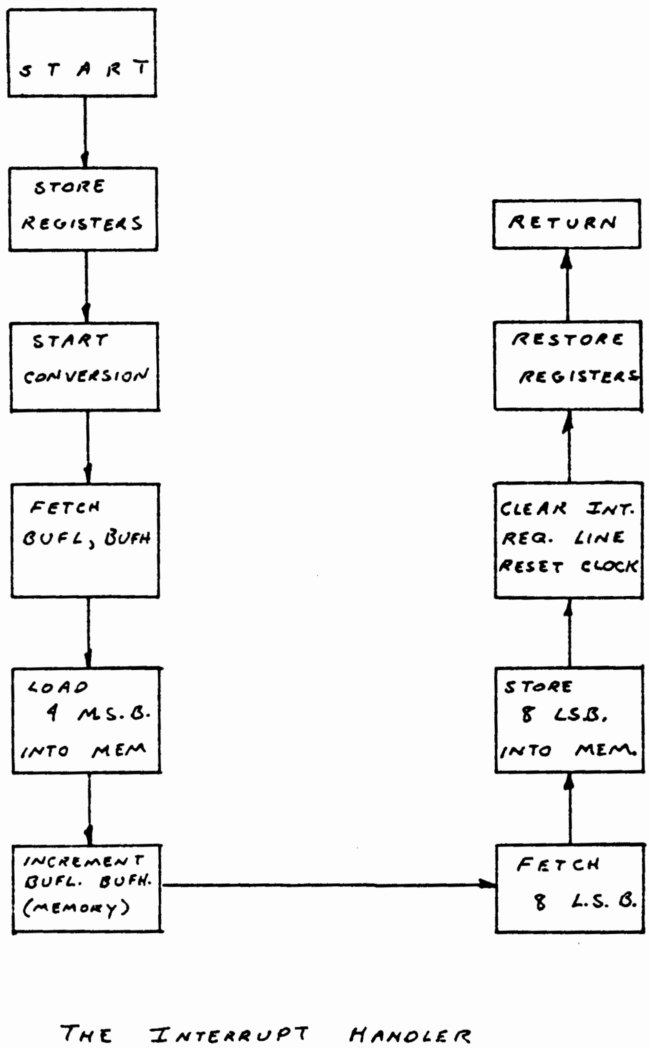

Figure 5. A flow chart describing the signal conversion/storage steps of the interrupt handler.

System Testing

The accuracy of the A/D convertor and the functioning of the system as a whole was tested by digitizing a 100 Hz sine wave supplied by a Tektronix TM-503 signal generator. A 100 Hz signal was chosen because it represented twice the frequency expected from the pressure transducer and was decided to be a good test of the convertor accuracy and the precision of the real-time clock. Fig. 6 shows a plot of the sine wave and a superposition of the data points resulting from the conversion.

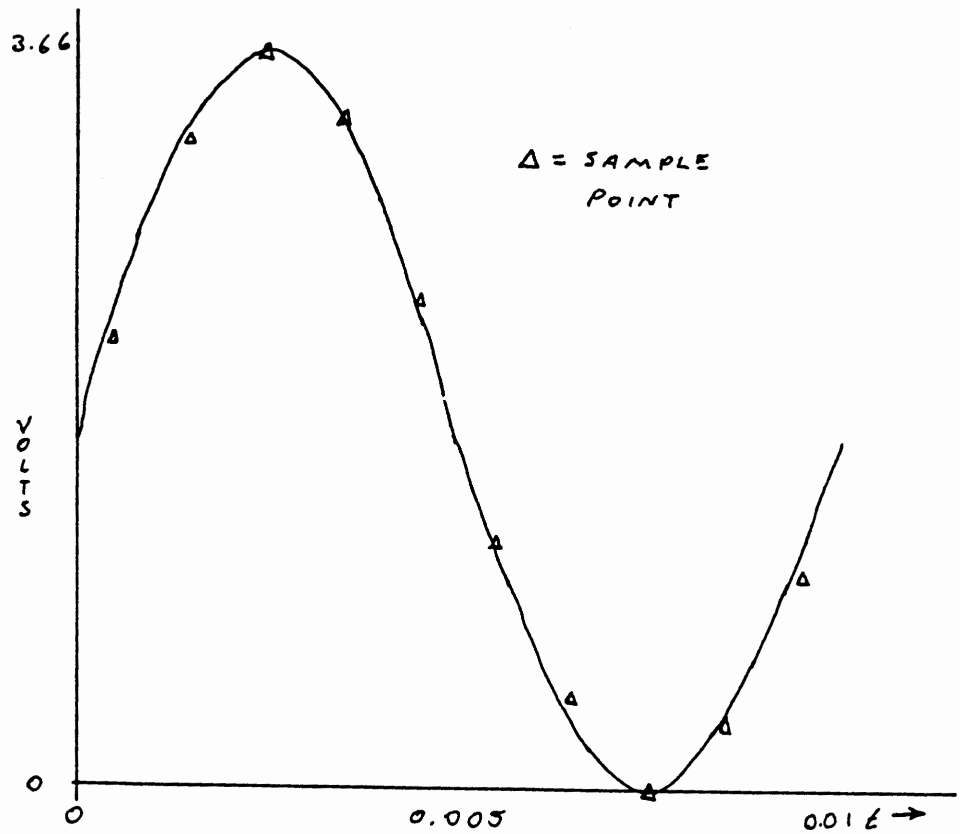

Figure 6. Digital representation plotted against the true 100 Hz sine wave. Sampling rate is 0.001 sec.

THEORY OF ANALYSIS

The underlying principles of the oscillometric method would indicate that much information can be obtained from the cuff pressure oscillations. So far the development of the oscillometric method into a standard technique for measuring systemic blood pressure has been hampered by the lack of reliable criteria to determine systolic and diastolic values.

Traditionally, relative amplitude measurements of the cuff pressure oscillations have been used with varying degrees of success. It has been demonstrated by Geddes et al (7) that there exists a correlation between the Korotkov sounds and the amplitude of the cuff pressure oscillations. To achieve acceptable accuracy with the amplitude criteria the recording of the cuff oscillations must be of exceptionally high fidelity. Most of the commercially available oscillometric units use a pneumatic cuff to apply occlusive pressures, and while this is convenient from a design and manufacturing standpoint the fidelity of the cuff oscillation recording suffers because of the compressibility of the air in the cuff. The signal undergoes a large reduction in amplitude and because air is an effective low-pass filtering medium the higher frequencies of the oscillations are drastically attenuated.

Bhattarai *et al* (8) devised new criteria for determining systolic and diastolic pressure. Using a hydraulic rather than pneumatic cuff, they were able to establish criteria for systolic and diastolic pressure based on the shape of the cuff pressure oscillations. The change in shape of the waveform suggests that the frequency content of the cuff oscillations also changes as a function of the external occlusive pressure and this in turn may lead to the development of new, spectral criteria for the determination of systemic blood pressure.

The spectral analysis of oscillometric data is a relatively new technique. It has been made feasible in recent years by improvements in analog/digital instrumentation and, more importantly, the digital computer algorithms that perform the calculations. A discussion of spectral analysis in general and its implementation on digital computers is presented in the next section.

SPECTRAL ANALYSIS

Information is gathered from the environment by transducers, so called because they convert one form of energy to a desired alternative form. Input energies can be of a thermal, mechanical, or electromagnetic nature but the output of a transducer is most often an electrical analog of the input.

Electrical signals can be easily manipulated to present the signal information in a manner that best illustrates different aspects of a system. It is common to speak of a signal as being presented in a particular domain. A domain is defined by the independent variable against which the signal information is plotted; a good example would be an oscilloscope, which plots input voltages as a function of the independent variable, time. The oscilloscope therefore presents a signal in the time domain. A plot of signal amplitude with respect to frequency is said to be mapped in the frequency domain. Functions in the frequency domain are often denoted by F(w) while time domain functions are labeled f(t).

In engineering applications it is often necessary to analyze signals in the time and frequency domain, depending on what characteristics of the system are of interest. In the analysis of rotating machinery, for example, the natural frequency of the system is crucial; such information is readily seen in the frequency domain. The study of the "water hammer" effect in piping, where time delays are of interest, is most easily examined in the time domain. There are many such examples in engineering but the most important fact to remember is that the transformation of a signal into another domain does not display new information but presents what information there is in another, desired alternative form.

Fourier Analysis

In 1807 the French physicist J.B. Fourier published a paper(10) in which he stated that most functions can be represented as a series of properly weighted mutually orthogonal basis functions. The basis functions used by Fourier were the Sine and Cosine functions and the series, known as the Fourier series, is given below.

$$f(t) = \frac{A_0}{2} + \sum_{p=1}^{\infty} \left\{ A_p \operatorname{Cos}(p\omega_0 t) + B_p \operatorname{Sin}(p\omega_0 t) \right\} \tag{1}$$

The coefficients A_p and B_p are given by:

$$A_p = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t) \operatorname{Cos}(p\omega_0 t)\, dt \tag{1a}$$

$$B_p = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t) \operatorname{Sin}(p\omega_0 t)\, dt \tag{1b}$$

It is fairly obvious that the Fourier series provides a mathematical relation between the time and frequency domains but the Fourier series is valid only under the following conditions:

1) The function must be absolutely integrable within the specified interval.

2) f(t) and f'(t) must be piecewise continuous within the interval.

3) f(t) must be periodic.

The first two constraints are easily met provided the signal to be analyzed is real in the mathematical sense and originates from some physical source. The third constraint can be overcome by evaluating the signal as the interval extends to infinity in both directions. As the analysis interval increases without bound the Fourier series becomes the Fourier integral given in equation (2).

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)\, e^{i\omega t}\, dt \qquad (2)$$

From the Fourier integral come the forward and inverse Fourier transforms.

$$F(\omega) = \int_{-\infty}^{\infty} f(t)\, e^{-i\omega t}\, dt \qquad (3a)$$

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)\, e^{i\omega t}\, d\omega \qquad (3b)$$

A derivation of the Fourier transforms from the Fourier series is given in Appendix B.

The forward Fourier transform maps each function value of the signal in a one-to-one manner from the time domain to the frequency domain and vice-versa for the inverse transform. The most useful quality of these transformations is that all of the phase and amplitude data of the original signal is present without the constraint that the signal be periodic.

The Discrete Fourier Transform (DFT)

The analytic relation given in equation (3a) would be satisfactory if the function f(t) were know in analytic form but, as so often with real signals an analytic equation is usually not available and the only way to execute the transform is through numerical methods. To do this we must descretize the continuous independent variable, t, and replace the integral sign with a summation.

$$F(\omega) = \sum_{n=-\infty}^{\infty} f(n\Delta t)\, e^{-i\omega(n\Delta t)}\, \Delta t \tag{4}$$

It is important to note here that equation (4) still contains all of the phase and frequency data of the original signal because the interval of analysis is still infinite. The realities of the physical world dictate that only a finite number of sample points can be obtained from the signal. Because taking a finite number of points essentially truncates equation (4) there will be an upper bound on how much frequency and phase information is retained in the transformation. This truncation of equation (4) yields the Discrete Fourier Transform (DFT):

$$F(m\Delta\omega) = \sum_{n=0}^{n-1} f(n\Delta t)\, e^{-i(m\Delta\omega)(n\Delta t)} \Delta t \tag{5}$$

where m is the maximum number of frequencies that can be represented in the frequency domain. The DFT, then, represents a numerical approximation of the Fourier integral over a finite interval consisting of N points spaced at Δt intervals. The entire interval can be expressed as a product of N and Δt.

$$T = N\Delta t \tag{6}$$

The maximum frequency present in the spectrum and the frequency resolution are functions of the sampling frequency. Shannon's Sampling Theorem (11) states that slightly more than two samples per cycle are required to uniquely define a sinusoid of a desired frequency. The mathematical statement of this theorem is given by:

$$F_{max} = \frac{1}{2\Delta t} \tag{7}$$

The frequency resolution, Δf, is expressed as:

$$\Delta f = \frac{1}{T} \tag{8}$$

F and f have units of Hz, T and t have units of seconds.

Pathologies of the DFT. Because the DFT is an approximation of the Fourier integral some errors in the values of the Fourier coefficients arise because of the truncation of the DFT. Two of the greatest sources of error are aliasing and the Gibbs phenomenon.

Aliasing occurs when frequencies higher than Fmax impersonate frequencies below Fmax by "folding back" around the maximum frequency, thereby creating a false peak in the frequency spectrum. Aliasing is caused by choosing a sampling frequency too low to accomodate all of the frequencies present in the original signal. In practice, aliasing is prevented by either increasing the sampling frequency or subjecting the incoming signal to a low-pass filter that attenuates all frequencies greater than Fmax.

The Gibbs phenomenon results directly from the truncation of the DFT. Truncation effectively introduces a discontinuity in the signal and as a result the Fourier coefficients calculated from the sample points in the immediate neighborhood of the discontinuity overshoot their true values. As the number of sample points increases the oscillation decreases but never entirely disappears. The maximum amount of overshoot is found in the infinitesimal interval on either side of the discontinuity and has been shown to be 9% (12). The overshoot can be compensated for by applying an appropriate weighting function. One such function in common use is a time domain function called the

Hanning window. It is a combination of a Cosine function and a unit-rectangular window, and its main advantages are the simplicity of construction and the significant reduction of overshoot at the discontinuities associated with the edges of the sample window. Fig. 7 illustrates the rectangular and cosinusoidal construction of the Hanning window.

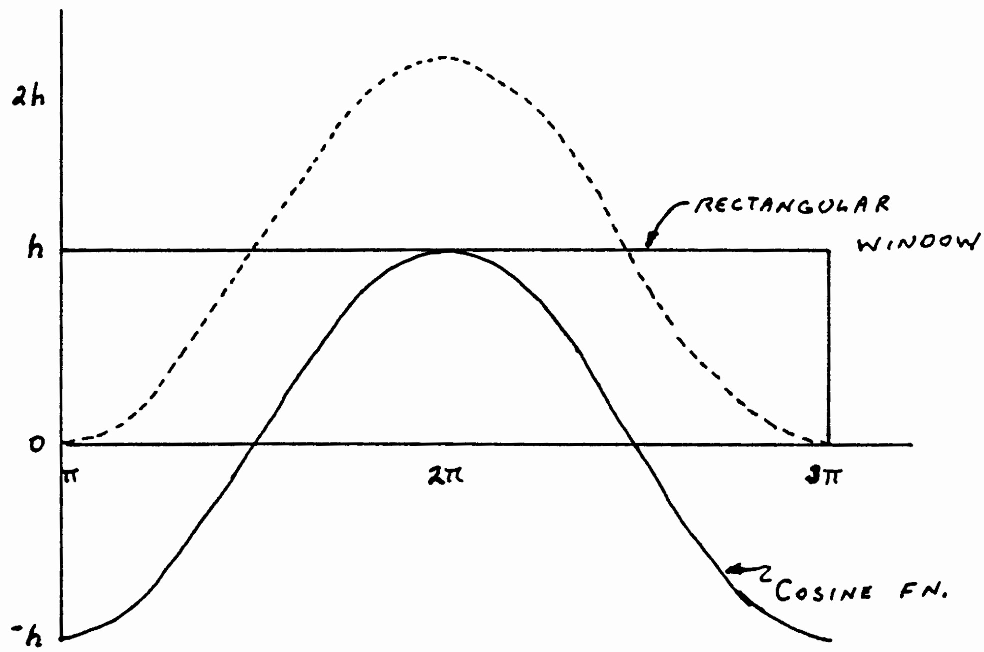

Figure 7. The Hanning window. The Hanning function is a graphical addition of the Cos function and unity.

The Fast Fourier Transform (FFT)

The DFT is perfectly adequate for calculating Fourier coefficients from sampled data but as N, the number of sample points, increases the total number of arithmetic operations increases as the square of N. It is easily seen that to obtain accurate Fourier coefficients of a sampled signal with the DFT as described above the calculation time and cost soon become prohibitive. In addition the round-off and truncation error of each individual operation increases the error at every step and unless the precision of the computing machine is very great unacceptable errors in the resulting Fourier coefficients will crop up regardless of how many sample points are used.

The DFT was made computationally practical with the introduction of the Cooly-Tukey Algorithm, or Fast Fourier Transform (FFT), in 1965 (13). The FFT drastically cuts down the number of computations from N^2 to $N \times \ln(N)$. This is accomplished by arranging the data in such a way that the matrix multiplications at every step produce intermediate results that make the subsequent calculation more efficient. For optimum performance the number of data points should be equal to some integer power of 2 e.g. 512, 1024, 2048, etc. Comparable performance can be obtained by using a radix-4 or radix-8 FFT rather than the radix-2 method described. There exist variations of this algorithm that reduce the number of operations even further but the mathematical manipulations are more complex to code and the advantages are significant only as the number of samples exceeds ten thousand (14).

It is important to remember that the FFT is still a

DFT and is subject to all the constraints and pathologies associated with the truncation of the DFT.

EXPERIMENTAL PROCEDURE

Frequent reference to the block diagram of the experimental set-up in Fig. 8 will aid in understanding the procedure. The method is the same regardless of whether water or air is used as the occlusive cuff actuator.

PRE-TEST PREPARATION

Data Acquisition System

The HOC is filled with de-aerated or distilled water and any air bubbles in the cuff, or the line leading from the cuff to the transducer, are purged by opening the escape valve on the HOC. The escape valve is then closed and most of the water is pumped from the HOC back to the reservoir.

The range calibration of the transducer and strip-chart recorder was done with a precision Bourdon tube pressure guage. The syringe pump was used to increase the pressure on the transducer and strip-chart levels were recorded every 0.2 psi ± 0.01 psi. Intermediate points between the known points were interpolated by using a clamped cubic spline algorithm and a Tektronix 4051 graphic computer. The chart range and the chart speed were +2.0 volts and 15 cm/sec, respectively, for all of the test sessions.

The programs are loaded from a program diskette by running A/D which in turn loads I-HANDL from the same diskette. The BASIC driver program A/D displays the appropriate prompt messages and the program diskette is replaced by an initialized data diskette.

Data Reduction System

The cut-off frequency of the ZTL processor is set to 30 Hz and the sampling rate is set to 10 mSec/sample. The triggering mode is internal and is set to the "single" mode with a positive slope. The input is AC coupled with an input gain of 0 dB.

The Tektronix 405X graphic computer is connected to the ZTL processor with a 25-dB, RS-232 protocol cable. An interface program is used to establish a communication link between the 405X computer and the ZTL processor and is available from the Portland State University Department of Mechanical Engineering. Once a communication link has been established the batch program ZONIC, listed in Appendix A, is stored in the processor's memory. A compatible hard-copy unit is connected to the Tektronix computer and is switched on well in advance of any test session to allow sufficient warm-up time.

Subject Preparation

The subject is seated and relatively motionless for five to ten minutes before the test session begins. During this time the pulse, respiration, and blood pressure stabilize at resting levels. The subject's pulse and an auscultatory measurement of the systolic and diastolic pressures are recorded and the suprasystolic and range pressure levels are then calculated.

DATA COLLECTION PROCEDURE

1) The programs A/D and ZONIC are run on the Apple and Tektronix computers, respectively.
2) The subject's forearm is inserted into the HOC and rubber end plugs are placed in either end of the HOC to prevent the bladder from ballooning outward during the test. The arm used for the test should be the same one used in the pre-test auscultatory measurement.
3) The syringe is filled with de-aerated or distilled water by drawing from an open reservoir. The stopcock at the tip of the syringe is switched and the HOC is inflated until the pressure rises to the point where a deflection of the strip-chart recorder pen is evident. The pump is stopped and the whole system is checked for leaks and any

air in the system is purged at this time.

4) The pump is re-started and, by using the variable speed control, the cuff pressure is slowly increased to the suprasystolic level. The strip-chart recorder is turned on and the speed control is adjusted minutely until the cuff pressure is steady, as evidenced by a steady line on the strip-chart record. Depress the carriage return on the Apple II+ and the "Arm" button on the ZTL processor. This starts the collection routines of the data acquisition and reduction systems. This point is then marked on the strip-chart record.

5) The ZTL processor will sample the AC coupled signal once every 10 mSec until 1024 points have been gathered, resulting in a record length of slightly over ten seconds. The Apple II+ collects the DC output of the transducer at the same time and when approximately ten seconds has elapsed the Apple system is turned off by depressing the carriage return. The pump is reversed and the HOC is depressurized.

6) The Apple II+ data is labeled and stored on a data diskette and the program A/D is cycled back to collect a new record.

7) The carriage return of the Tektronix computer is depressed, causing the just-gathered data to be

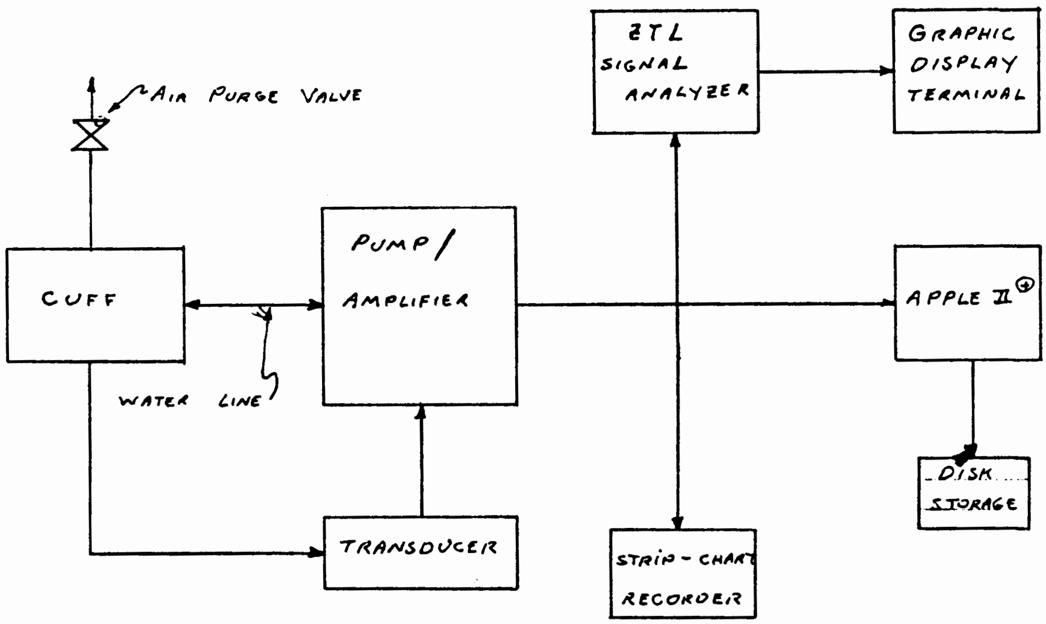

Figure 8. A block diagram of the experimental set-up used in this study.

copied into a secondary storage area, leaving the primary memory block free to accept a new input.

8) The pump is reversed and steps 4-6 are repeated.

9) Depressing the carriage return again causes the time domain plots of the two pressure records to appear on the screen of the Tektronix computer. A copy of these plots are obtained from the hard-copy unit.

10) The carriage return is pressed again and the spectral plots of the pressure records replace the

time domain plots on the screen. A copy of these plots are obtained as in the previous step.

11) The entire process is repeated for the range and the diastolic pressures.

EXPERIMENTAL RESULTS AND ANALYSIS

The 24 test subjects ranged in age from 21 to 59 years. Most subjects were caucasian males in their early twenties, in good health, with no known history of high blood pressure. Data was taken from two females, also in their early twenties. Resting systemic pressures, taken before and after every test session, ranged from 99/52 RA to 160/85 RA. Ten second samples from suprasystolic, systolic, diastolic, and an intermediate pressure level, known as a "range" pressure, were obtained from each subject. The test was repeated on select subjects, using air rather than water to inflate the HOC. The time domain and power spectral density functions were plotted for each test pressure.

TIME DOMAIN DATA

The shape of the cuff oscillations were grossly similar regardless of the amplitude or pressure level at which they were collected. Fig. 9 shows a typical plot of a ten-second sample collected from a young male at a cuff pressure of 60 mm Hg. There is a slight rise in pressure at the beginning of each cardiac cycle, followed by a much smaller and slightly broader peak. The pressure then drops to zero and the cycle repeats. The cuff pulse shape detected at the transducer strongly resembles the arterial pulse shapes obtained via intra-arterial probes (4).

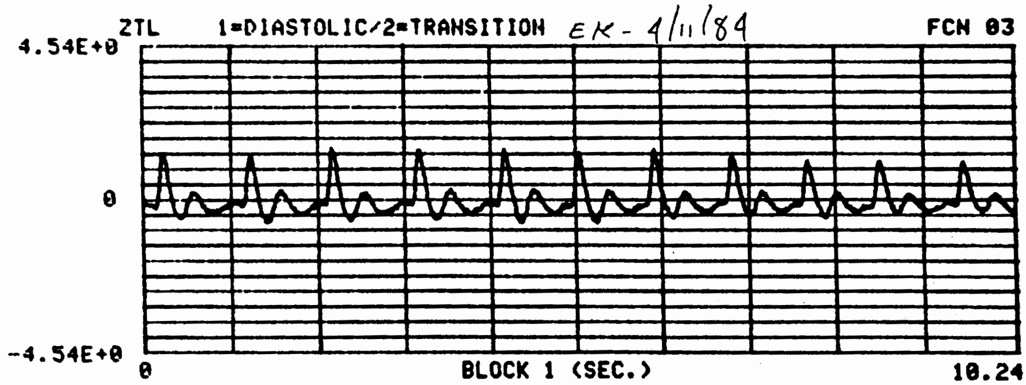

Figure 9. A ten-second pressure record of the cuff oscillations. The occlusive pressure is 60 mm Hg.

The cuff oscillation amplitudes varied as a function of the external hydraulic or pneumatic pressure exerted on the forearm. Table I gives the average peak amplitudes of the cuff oscillations for each subject at the four test levels. The average amplitude and standard deviation of the cuff oscillations are given in Table II. The largest oscillations were observed at the range and diastolic pressure levels while the smallest oscillations were found in the suprasystolic and systolic records.

TABLE I

CUFF OSCILLATION AMPLITUDES IN mm Hg FOR EACH SUBJECT AT THE FOUR TEST LEVELS

SUBJECT	SUPRASYSTOLIC	SYSTOLIC	RANGE	DIASTOLIC
JW	0.908	0.953	1.362	0.409
RL	0.681	0.681	0.908	0.499
RH	0.999	1.044	1.725	0.681
MC	0.590	0.726	0.953	0.454
FB	0.454	0.681	0.908	0.454
JP	0.863	1.090	1.135	0.908
JJ	0.409	0.454	0.363	0.363
SS	0.590	0.454	0.863	1.044
DS	0.722	0.999	1.362	0.409
WP	*	*	*	1.589
TB	*	*	2.315	1.725
JZ	*	*	2.043	1.952
DW2	0.363	0.363	0.499	0.681
ST	0.545	0.817	0.999	0.499
EK	0.772	0.953	1.186	1.362
JB	0.182	0.227	0.227	0.136
KH	0.953	1.090	1.407	0.681
OM	0.182	0.272	0.409	0.227
PC	0.363	0.454	0.681	0.863
DW	0.636	0.817	1.090	0.636
RA	0.454	0.723	0.863	1.135
NH	0.409	0.454	0.999	0.999
CP	0.318	0.454	0.454	0.499
AN	0.454	0.454	0.999	0.953

* - Indicates incomplete data

SPECTRAL DATA

The autospectrum of a signal is a measure of the energy distribution as a function of frequency. The scale

TABLE II

AVERAGE AMPLITUDE AND STANDARD DEVIATION
OF THE FOUR TEST LEVELS

LEVEL	AVG.	STD. DEV.
SUPRASYSTOLIC	0.57	0.24
SYSTOLIC	0.67	0.28
RANGE	1.05	0.54
DIASTOLIC	0.79	0.48

of the plots are normalized with respect to the peak amplitude of the signal in the time domain. Each data point of the raw data is mapped by the forward Fourier transform into the frequency domain and the autospectrum is calculated from the derived Fourier coefficients.

Common Characteristics

Each of the autospectra were unique but some features were found to be present regardless of the subject or the pressure level at which the data were taken. The spectra showed energy concentrations at distinct peaks spaced at regular intervals. The first four peaks were estimated, by examining the area under the spectral curve, to contain approximately 90% of the total signal energy. After the fourth peak the amplitudes of the subsequent peaks drop off to levels indistinguishable from noise levels. Significant peaks at 20 and 40 Hz were also observed in each spectra. A typical set of spectra is shown in Fig. 10.

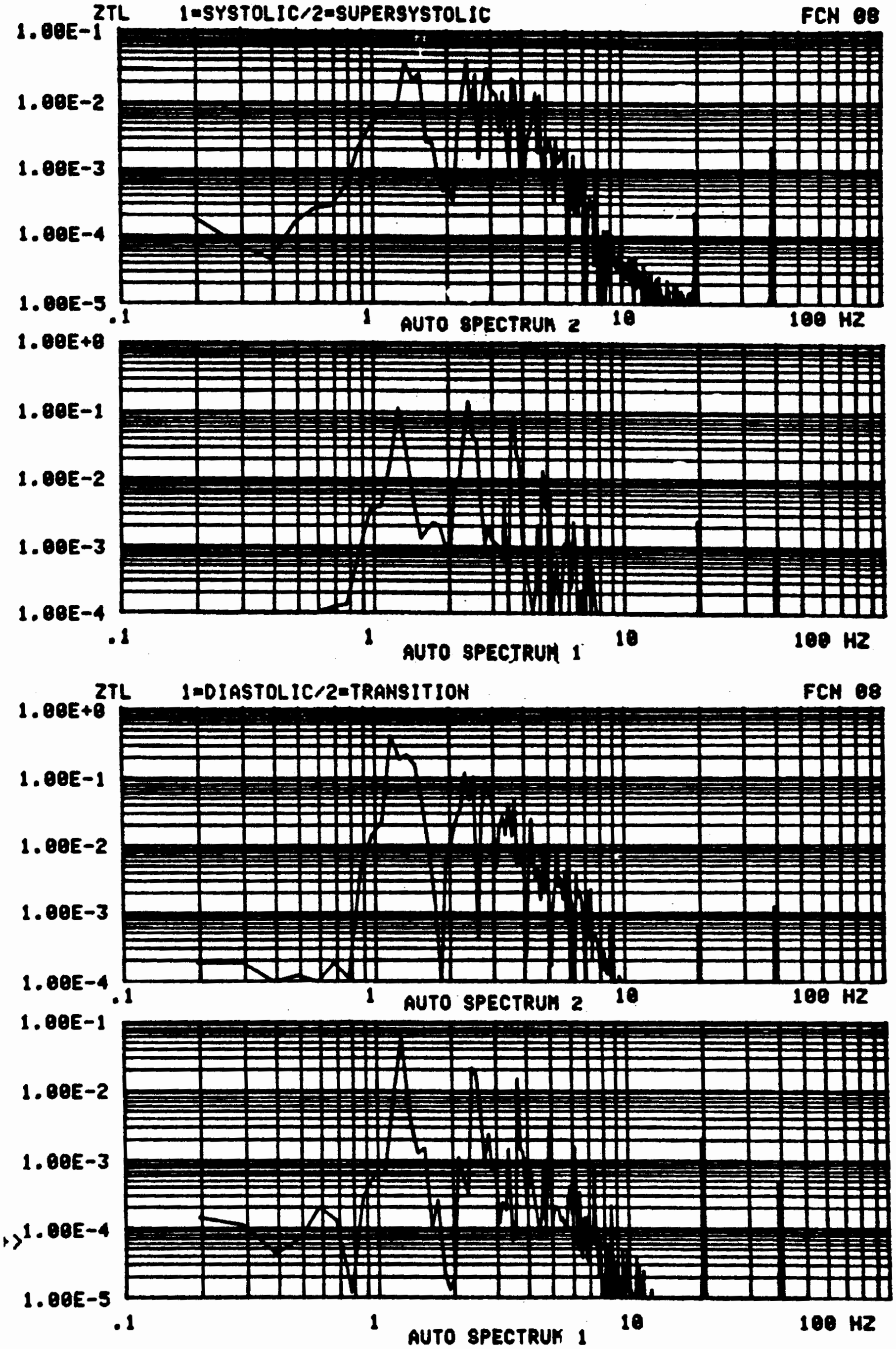

Figure 10. Autospectra of the four test levels. From top: suprasystolic, systolic, range, and diastolic pressures. Note 20 and 40 Hz peaks.

spectra taken during pneumatic tests show a marked decrease in the number of higher frequencies (greater than 10 Hz) present and an attenuation of approximately one order of magnitude in all frequencies.

Unique Characteristics

Along with the shared characteristics discussed above each pressure level displayed minor variations of the spectral plot with respect to peak formation, additional peaks, and absolute and comparative peak amplitudes.

At suprasystolic, systolic, and range pressures the amplitudes of the second and third peaks of the autospectra often exceeded the amplitude of the first peak. As the pressure was decreased to diastolic levels the energy contained in the second and third peaks fell below the energy level of the first peak. At suprasystolic levels many minor peaks were observed to be superimposed on the major peaks of the spectra. At lower pressure levels the peaks generally became smoother and better defined. Intermediate peaks, located between the first and second major peak, were consistently observed at suprasystolic and systolic pressures but were absent at lower levels.

The spectra obtained from the tests performed with a pneumatically-actuated cuff possessed the same characteristics as those derived from the hydraulic tests, the main difference being that the higher frequencies were either totally absent or greatly attenuated. Fig. 11 is a comparison between pneumatic and hydraulic spectra obtained from the same subject at the same time. On casual inspection the pneumatic and hydraulic spectra show little difference but the attenuation of the pneumatically collected signal is evident when the vertical scales of the spectra are compared; the scaling of the pneumatic spectra ranges from 10^{-6} to 10^{-2} while the hydraulic spectra is plotted from 10^{-5} to 10^{-1}, representing a change in signal strength of a whole order of magnitude.

Summary of Results

We can now summarize the key observations of the time domain data and the autospectra of the four test pressures. For the time domain data the significant observations are summarized below.

1) The shape of the cuff oscillations was grossly similar regardless of the external occlusive pressure level.
2) Cuff oscillations collected at range pressures showed the largest amplitudes followed, in decreasing amplitude by the oscillations of the diastolic, systolic, and suprasystolic levels.

The spectral data are more revealing in that the frequency data show greater variations from one test pressure

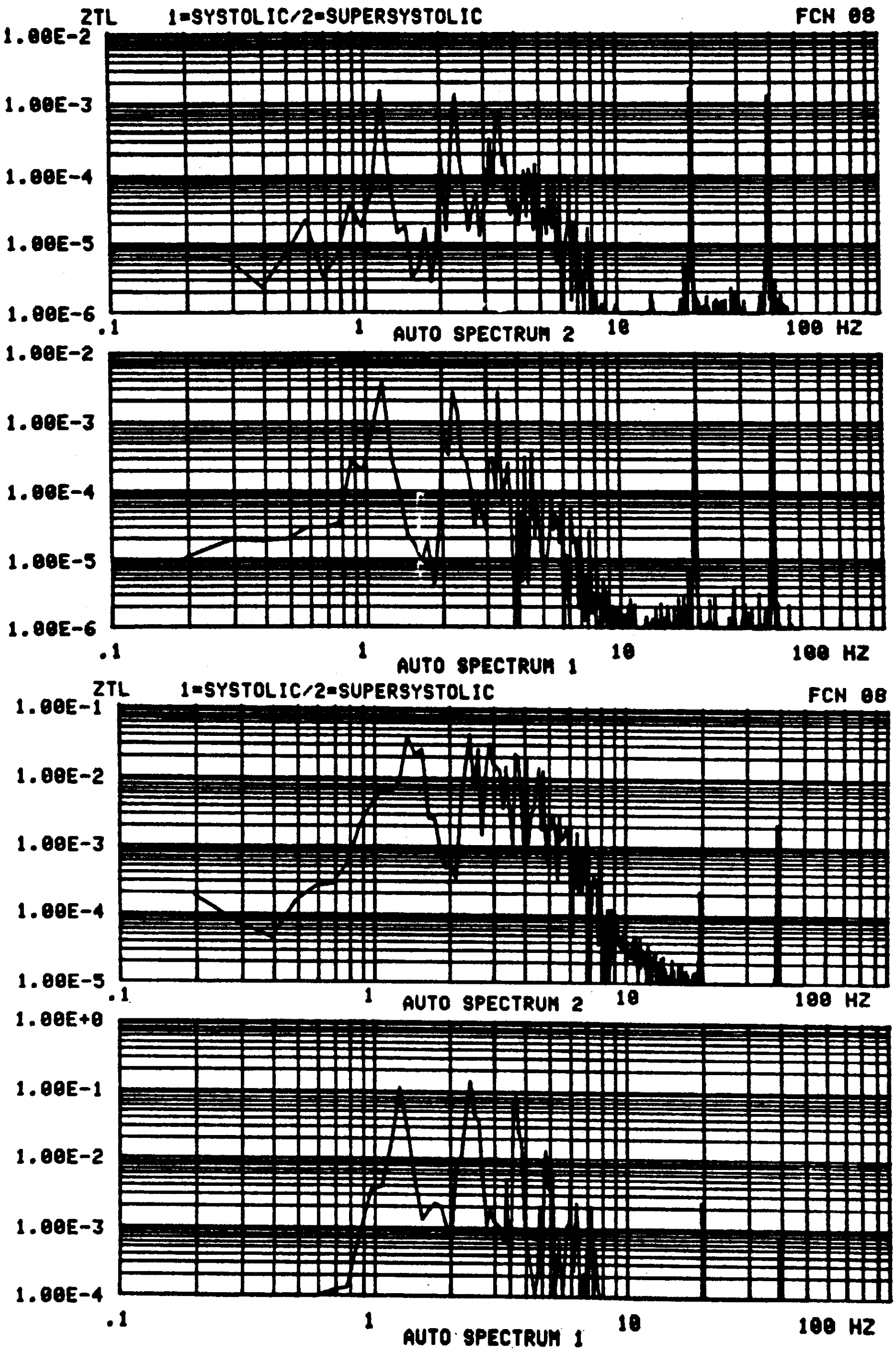

Figure 11. Comparison between hydraulic and pneumatically gathered spectra. The top two spectra are pneumatic, the bottom two hydraulic. Note the change in scale between the two spectral plots.

to the next. The most consistent characteristics are:

1) All the spectra display three or four major peaks. At suprasystolic and systolic pressures, some minor peaks are superimposed on the major peaks.
2) The autospectra of the suprasystolic and systolic data are less energetic than the data obtained from the range and diastolic levels.
3) The major peaks become more well-defined and separated as external pressure is decreased.
4) Approximately 90% of the signal energy is contained in the first three peaks.
5) At suprasystolic, systolic, and range pressures the second and third peak amplitudes often are equal to, or exceed, the amplitude of the first peak.
6) An intermediate peak, between the first and second major peaks, appears at suprasystolic and systolic levels but is absent at lower pressures.

ANALYSIS OF RESULTS

The general shape and characteristics of the spectra are consistent with the Fourier transformation of a simplified pulse and with the results of other mammalian studies (15). The first major peak of the spectral data is the pulse frequency of the circulatory system and the subsequent peaks are hamonics of the pulse frequency occuring at integral multiples of the heart rate. The strength of the signal increased as the external occlusive pressure decreased until the cuff pressure reached diastolic levels whereupon the amplitude of the cuff oscillations became significantly smaller.

Noise Analysis

The significant sources of electrical noise were thought to be the syringe pump motor, the Action Pak strain gage amplifier, and the fan motors of the ZTL processor. Because the input signal was low-pass filtered at a cut-off frequency of 30 Hz the amplifier and pump noises, assumed to be concentrated at approximately 60 Hz because of the AC power source, were not thought to contribute any spurious signals to the bandwidth under consideration. The 20 and 40 Hz peaks, present in every spectrum collected, were the main sources of concern because these frequencies occupied a very narrow bandwidth and their amplitudes were two or three orders of magnitude greater than those of neighboring frequencies.

Autospectra were derived at the regular experimental sampling rate, with all the equipment activated but with no arm inserted in the cuff (zero pressure) in order to analyze system noise. The spectra of the system noise, with the pump motor running at high and low speed settings, are shown in Fig. 12. At low speeds the pump motor introduces virtually no noise to the signal input; the 20 and 40 Hz peaks, as well as some low frequency energy, were the only signals present. At high-speed pump operation the noise of the drive motor manifests itself as a very low amplitude signal containing a large number of roughly equal-amplitude frequency components. The 40 Hz peak was strongly suspected to originate from within the ZTL processor; a cooling fan was later found to be operating at 2400 rpm and this was assumed to be the source of the noise. It is believed, because of the amplitude similarity, the 20 Hz peak is in some way related to the 40 Hz peak.

Systolic and Diastolic Criteria

An objective criterion for the determination of the systolic point may have been found during the examination of the almost one hundred spectra collected. The proposed criterion for systolic pressure is the presence of a spectral peak midway between the pulse frequency and the first harmonic. In 81% of the systolic or suprasystolic spectra this peak was observed at an average suprasystolic pressure of +5.4 mm Hg above the auscultatory measurement. At the range pressure levels this intermediate peak was present in only 20% of the spectra collected. Fig. 13 gives a good example of the suprasystolic peak and its ab-

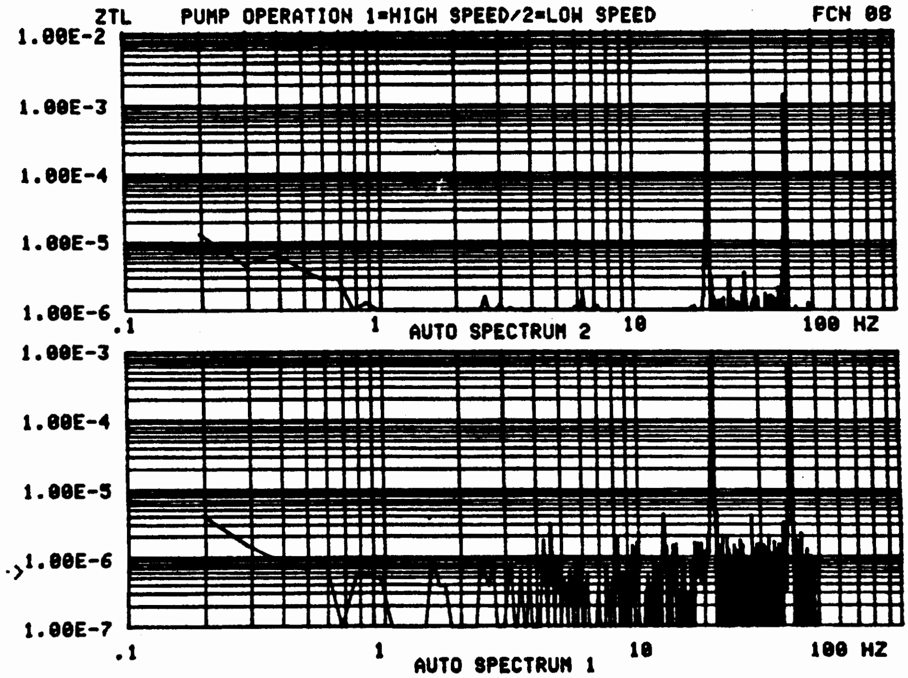

Figure 12. Noise spectra of the experimental system with atmospheric pressure at the transducer.

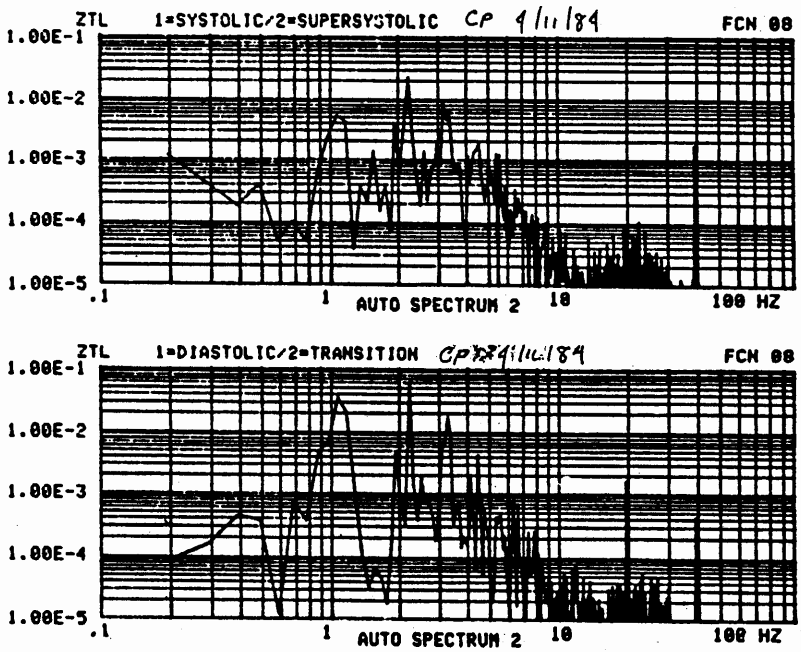

Figure 13. The intermediate spectral peak present at suprasystolic levels (top) and absent at range pressures (bottom).

sence at the range level. This intermediate peak was observed at the diastolic pressure only half as often (40%) as at the systolic level. Table III gives a subject-by-subject breakdown of the presence or absence of the systolic, diastolic, and range level peaks.

Conclusions and Recommendations

The objective of this study was to examine arterial pulsations obtained via a hydraulic occlusive cuff and arrive at objective criteria for systolic and diastolic systemic pressure. The raw data were digitized and a discrete Fourier transform was performed to ultimately obtain the component frequencies of the sampled data. The final conclusions are enumerated below:

1) The hydraulic occlusive cuff produces data records of superior fidelity to those obtained with pneumatically actuated occlusive cuff records. This was verified by actually collecting data from the same subject in the same test session, once with water and again with air as the cuff actuating medium. The hydraulic records were found to be of significantly greater amplitude with the retention of the higher frequencies that were absent from the pneumatic records.
2) A strong correlation was found between the external occlusive pressure and the presence of

TABLE III

FREQUENCY OF SYSTOLIC, RANGE, AND DIASTOLIC PEAKS

SUBJECT	SYSTOLIC	RANGE	DIASTOLIC
JW	+6.0	-	-
RL	-	+	-3.0
RH	+5.0	+	-
MC	+3.0	-	-6.0
FB	-	-	-
JP	+5.0	-	-
JJ	-	-	-1.0
SS	+5.0	+	-2.0
DS	+6.0	-	-
WP	*	*	*
TB	*	*	-
JZ	*	-	-
DW2	+11.0	-	-
ST	+9.0	+	+1.0
EK	+8.0	-	-2.0
JB	+5.0	-	-
KH	+4.0	-	-
OM	+4.0	-	-
PC	+2.0	-	-1.0
DW	0.0	-	-2.0
RA	-	+	+5.0
NH	+8.0	-	-
CP	+8.0	-	0.0
AN	+4.0	-	-

* - Represents incomplete data.
+/- - Presence/absence of range peak.
All pressures are relative to systolic and diastolic pressures and are measured in mm Hg.

intermediate peaks midway between the pulse frequency and the first harmonic. This peak was detected at a suprasystolic level of +5.4 mm Hg and is concluded to be a positive indication of systolic systemic pressure.

3) A similar criterion could not be formulated for

diastolic pressure but it was observed that the first and second harmonics displayed significantly lower amplitudes at the diastolic level than at the other three test pressures.

This study was a relatively simple and straightforward attempt at the spectral analysis of recorded blood pressure pulses detected non-invasively. The following recommendations should clarify the direction further research in this area should take:

1) Development of a physical or mathematical model of an arterial segment is a must. One simple model would be the assumption that the arterial wall is a thin elastic strip bounded at both ends and possessing some initial displacement, due to an external force, along its length.

2) Intra-arterial experiments, with similar equipment on human subjects during arterial catheterization.

3) Development of a high-speed FFT algorithm for personal computers. The data could be stored and reduced by the same computer. This would go a long way in making any spectral criterion clinically acceptable by simplifying the amount of equipment needed to identify the spectral characteristics peculiar to systolic and diastolic pressures.

4) Investigation of other mathematical signal processing techniques e.g. digital differentiation of the digitized signal.

5) Development of a second-generation hydraulic occlusive cuff.

REFERENCES

1) American Heart Association, "Heart Facts 1984" Publication #55-005-H, 1984

2) American Heart Association, "High Blood Pressure" Publication #50-052-A, 1980

3) Kirkendall, W.M., et al, "Recommendations for Human Blood Pressure Determination by Sphygmomanometers", American Heart Association Publication #70-019-B, 1980

4) Guyton, A.C., Textbood of Medical Physiology 4th ed., Saunders, Philadelphia, 1971

5) Holman, J.P., Experimental Methods For Engineers 3rd ed., McGraw-Hill, New York, NY, 1978

6) Howell, W.H., Brush, C.E., "A Critical Note Upon Clinical Methods of Measuring Blood Pressure" Boston Medical and Surgical Journal, pp. 146-31 1901

7) Geddes, L.A., et al "Characterizations of the Oscillometric Method for Measuring Indirect Blood Pressure", Annals of Biomedical Engineering, Vol. 10, pp. 271-80, 1982

8) Bhattarai, K.R., "Investigation of Blood Pressure Measurement Using a Hydraulic Occlusive Cuff", MS/EAS thesis, Portland State University, 1982

9) Apple Computer, Inc., Apple II Reference Manual Cupertino, CA., Apple Product #A2l0001A (030-0004-01) 1979

10) Grattan-Guinness, I., Joseph Fourier 1768-1830 The MIT Press, Cambridge, MA., 1972

11) Zonic Technical Laboratories, "Instruction Manual /DMS 5003 System/System Operation", 3 Vols., ZTL Inc., Cincinnati, OH 1978

12) Bracewell, R.N., The Fourier Transform and its Applications 2nd ed., McGraw-Hill, New York, NY 1978

13) Cooley, J.W., Tukey, J.W., "An Algorithm for the Machine Calculation of Complex Fourier Series", Mathematics of Computation, 1965, 19, No. 90, pp. 297-301

14) Elliott, D.F., Rao, R.K., Fast Transforms/ Algorithms, Analyses, Applications, Academic Press, New York, NY, 1982

15) Daniels, F.H., et al "Spectral Analysis of Arterial Blood Pressure in the Rat", IEEE Trans. on Biomed. Engineering, Vol BME-30, No. 3, March 1983

APPENDIX A

SOFTWARE LISTINGS

Given below are listings of the computer programs used in this study.

A/D (BASIC Driver Program)

A/D is a prompting program that controls the operation of the data acquisition subroutines and stores tehdata on 5¼" floppy diskettes. It should be used in conjunction with an Apple II+ with at least 48K of RAM. It is written in Applesoft and details of the programming language can be found in the reference material (9).

```
 10 REM***A/D PROGRAM VERSION 1.0
 20 REM***1/4/84
 30 D$=CHR$(4)
 40 E$=","
 50 F$="A3072"
 60 V$="L"
 70 PRINT D$"BLOAD A/D #1.3"
 80 HOME:PRINT:PRINT:PRINT:PRINT
 90 PRINT "A/D CHANNEL = 0"
100 PRINT:PRINT:PRINT:PRINT
110 PRINT "BEGINNING ADDRESS = 3072"
120 PRINT:PRINT:PRINT:PRINT
130 PRINT "PRESS RETURN TO INITIALIZE INTERRUPTS";
140 INPUT Z$
150 REM***CALL TO ASSEMBLY INITIZALIZER
160 CALL 768
170 HOME:PRINT:PRINT:PRINT:PRINT
180 PRINT "PRESS RETURN TO COLLECT DATA";
190 INPUT Z$
200 PRINT:PRINT:PRINT:PRINT
```

```
210 REM***START CLOCK
220 L=PEEK(-16139)
230 HOME:PRINT:PRINT:PRINT:PRINT
240 INPUT Z$
250 REM***CALL ASSEMBLY FINISH
260 CALL 887
270 REM***STOP CLOCK
280 L=PEEK(-16138)
290 HOME:PRINT:PRINT:PRINT:PRINT
300 A=PEEK(974)*256+PEEK(973)
310 REM***A+ENDING DATA ADDRESS
320 PRINT "ENDING DATA ADDRESS = ";A
330 D=A-3072
340 PRINT:PRINT:PRINT:PRINT
350 PRINT "DATA MEMORY LENGTH = ";D
360 PRINT:PRINT "SAVE FILE(Y/N)";
370 INPUT Z$
380 IF Z$="Y" GOTO 430
390 PRINT:PRINT "COLLECT NEW RECORD (Y/N)";
400 INPUT Z$
410 IF Z$="Y" GOTO 80
420 END
430 PRINT:PRINT "FILE NAME = ";
440 INPUT N$
450 PRINT:PRINT "FILE LENGTH = ";
460 INPUT M$
470 PRINT D$"BSAVE";N$;E$;F$;E$;V$;M$
480 HOME:VTAB 4: GOTO 390
```

I-HANDL

The machine language programs are written in 6502 assembly code. A key to these mnemonics is found in the reference material (9).

MEMORY ADDRESS	MNEMONIC		OPCODES		
0300	SEI		78		
0301	PHA		48		
0302	TXA		8A		
0303	PHA		78		
0304	TYA		98		
0305	PHA		48		
0306	LDA	#$00	A9	00	
0308	STA	$03CD	8D	CD	03
030B	LDA	#$0C	A9	0C	

MEMORY ADDRESS	MNEMONIC		OPCODES		
030D	STA	$03CE	AD	CE	03
0310	LDA	#$26	A9	26	
0312	STA	$03FE	8D	FE	
0315	LDA	#$03	A9	03	
0317	STA	$03FF	8D	FF	03
031A	LDA	#$01	A9	01	
031C	STA	$C0F9	8D	F9	C0
031F	PLA		68		
0320	TAY		A8		
0321	PLA		68		
0322	TAX		AA		
0323	PLA		68		
0324	CLI		58		
0325	RTS		60		
0326	LDA	$45	A5	45	
0328	PHA		48		
0329	TXA		8A		
032A	PHA		48		
032B	TYA		98		
032C	PHA		48		
032D	LDA	#$00	A9	00	
032F	STA	$C0A0	8D	A0	C0
0332	LDA	$03CD	AD	CD	03
0335	STA	$0347	8D	47	03
0338	LDA	$03CE	AD	CE	03
033B	STA	$0348	8D	48	03
033E	NOP		EA		
033F	NOP		EA		
0340	NOP		EA		
0341	NOP		EA		
0342	NOP		EA		
0343	LDA	$C0A1	AD	A1	C0
0346	STA	$03CC	8D	CC	03
0349	INC	$03CD	EE	CD	03
034C	BNE	$0351	D0	03	
034E	INC	$03CE	EE	CE	03
0351	LDA	$03CD	AD	CD	03
0354	STA	$0361	8D	61	03
0357	LDA	$03CE	AD	CE	03
035A	STA	$0362	8D	62	03
035D	LDA	$C0A0	AD	A0	C0
0360	STA	$03CC	8D	CC	03
0363	INC	$03CD	EE	CD	03
0366	BNE	$036B	D0	03	
0368	INC	$03CE	EE	CE	03
036B	LDA	$C0F7	AD	F7	C0
036E	LDA	$C0F8	AD	F8	C0
0371	PLA		68		

MEMORY ADDRESS	MNEMONIC		OPCODES		
0372	TAY		A8		
0373	PLA		68		
0374	TAX		AA		
0375	PLA		68		
0376	RTI		40		
0377	PHA		48		
0378	TXA		8A		
0379	PHA		48		
037A	TYA		98		
037B	PHA		48		
037C	LDA	#$00	A9	00	
037E	STA	$C0F9	8D	F9	C0
0381	LDA	$C0F7	AD	F7	C0
0384	LDA	$C0F8	AD	F8	C0
0387	LDA	#$65	A9	65	
0389	STA	$03FE	8D	FE	03
038C	LDA	#$FF	A9	FF	
038E	STA	$03FF	8D	FF	03
0391	PLA		68		
0392	TAY		A8		
0393	PLA		68		
0394	TAX		AA		
0395	PLA		68		
0396	CLI		58		
0397	RTS		60		

ZONIC

This program, written in the batch programming language of the ZTL processor, controls the reduction and display of the raw data. Details on the programming language are given in the reference material (11).

```
1) QR 10
2) QD 1 1 4.5432
3) QD 2 1 4.5432
4) QLIST
5) !
6) SUPRASYSTOLIC INPUT
7) H
8) I 1 1
9) Z 2 0 1024
```

```
10) C 1 2
11) !
12) SYSTOLIC INPUT
13) H
14) I 1 1
15) TITLE 1=SYSTOLIC/2=SUPRASYSTOLIC
16) B
17) DL 3
18) H
19) F
20) B
21) DL 8 1
22) H
23) B
24) !
25) TRANSITION INPUT
26) H
27) I 1 1
28) Z 2 0 1024
29) C 1 2
30) !
31) DIASTOLIC INPUT
32) H
33) I 1 1
34) TITLE 1=DIASTOLIC/2=TRANSITION
35) B
36) DL 3
37) H
38) F
39) B
40) DL 8 1
41) END
```

APPENDIX B

DERIVATION OF THE FOURIER TRANSFORM

The derivation of the forward and inverse Fourier transforms is relatively straightforward. We begin with the expression for the Fourier series given earlier in the text but repeated below.

$$f(t) = \frac{A_0}{2} + \sum_{p=1}^{\infty} \left\{ A_p \cos(p\omega_0 t) + B_p \sin(p\omega_0 t) \right\} \qquad \text{(B.1)}$$

T is the interval of analysis in seconds. The coefficients A_p and B_p are given by:

$$A_p = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t) \cos(p\omega_0 t)\, dt \qquad \text{(B.2a)}$$

$$\omega_0 = \frac{2\pi}{T}\ ; \quad p = 1, 2, 3, \ldots$$

$$B_p = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t) \sin(p\omega_0 t)\, dt \qquad \text{(B.2b)}$$

The Fourier series can be rewritten in complex form by using the following identities for sine and cosine:

$$\sin(p\omega_0 t) = \frac{e^{ip\omega_0 t} - e^{-ip\omega_0 t}}{2i} \qquad \text{(B.3a)}$$

$$\mathrm{Cos}(p\omega_\circ t) = \frac{e^{ip\omega_\circ t} + e^{-ip\omega_\circ t}}{2} \tag{B.3b}$$

Substituting (B.3a) and (B.3b) into (B.1) yields the complex form of the Fourier series.

$$f(t) = \sum_{p=-\infty}^{\infty} C_p\, e^{ip\omega_\circ t} \tag{B.4}$$

The coefficient C_p is given by:

$$C_p = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\, e^{-ip\omega_\circ t} \tag{B.5}$$

By changing the notation slightly the Fourier series can be written in the following manner.

$$f(t) = \sum_{p=-\infty}^{\infty} \frac{1}{T}(TC_p)\, e^{ip\omega_p t} = \frac{1}{2\pi}\sum_{p=-\infty}^{\infty} (TC_p)\, e^{i\omega_p t}\, \Delta\omega_p \tag{B.6a}$$

WHERE: $\omega_p = p\omega_\circ$; $(p+1)\omega_\circ - p\omega_\circ = \omega_\circ = \frac{2\pi}{T} = \Delta\omega_p$

$$TC_p = \int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)\, e^{-i\omega_p t}\, dt \tag{B.6b}$$

Now we can let the period T increase without bound and as we do so the discrete value w_p becomes the continuous variable w. By taking the limit of (B.6a) and (B.6b) the summation sign is replaced with an integral.

$$f(t) = \lim_{\substack{T\to\infty \\ \omega_p\to 0}} \frac{1}{2\pi} \sum_{p=-\infty}^{\infty} (T c_p) e^{i\omega_p t} \Delta\omega_p = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{i\omega t} d\omega \qquad \text{(B.7a)}$$

$$F(\omega) = \lim_{\substack{T\to\infty \\ \omega_p\to 0}} \int_{-\frac{T}{2}}^{\frac{T}{2}} f(t) e^{-i\omega_p t} dt = \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt \qquad \text{(B.7b)}$$

Equations (B.7b) and (B.7a) are the forward and inverse Fourier transforms, respectively.