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A microcomputer based non-invasive cardiopulmonary monitor using a microwave interferometer

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ABSTRACT

Title of Thesis : A MICROCOMPUTER BASED NON-INVASIVE CARDIOPULMONARY MONITOR USING A MICROWAVE INTERFEROMETER

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With a *microwave interferometer* the vibrational velocity of the anterior (front), as well as posterior (back) chest wall can be monitored and recorded. The recorded signals are a reflection of the *mechanical cardiac activity* within the chest cavity, as opposed to *Electrocardiogram* (ECG) which is a reflection of the electrical cardiac activity. The interferometer recordings are obtained with no physical contact between the instrument and the subject. Moreover, the subject can be fully clothed since microwave energy readily passes through normal dry clothing.

A microwave interferometer that is capable of detecting the *vibrational velocity* of the surfaces of the chest cavity (anterior and posterior) has been described in detail in the thesis. The objective of this research work is to *monitor*, *record* and *analyze* these vibrational characteristics of the chest wall using the microwave interferometer from co-operative healthy, normal subjects, both males as well as females, and thus to evaluate the possibility of using this instrument as a *non-invasive* and *non-contacting cardiopulmonary monitor*. The recordings from an ECG are very well understood by doctors and engineers today. By studying the signals obtained from the microwave interferometer with the ECG as a timing reference, and bearing in mind that certain mechanical cardiac events, such as valves opening and closing occur at certain points in the RR interval of the ECG, an attempt has been made to identify a common 'signature' or repetitive vibration pattern of the chest wall in normal, healthy male and female subjects. The interferometer data from one subject is *autocorrelated* to accentuate those features that are repetitive and also to attenuate the non-repetitive features. High amplitude velocity peaks are noticed at similar times within each cardiac cycle . In order to relate the timing of the peaks in the raw interferometer signal to the timing of certain known events in the cardiac cycle, such as the R wave of the ECG (recorded simultaneously), the interferometer signal is *cross-correlated* with a pulse train obtained by filtering out the R peaks from the ECG of the same subject. With the existing knowledge of the timing of mechanical events within an RR interval an attempt is made to relate the high-velocity peaks to these mechanical events.

The interesting question is raised whether this technique can be used to detect those cardiac abnormalities that significantly alter the mechanical coupling of the cardiac musculature to the chest wall. This instrument may also prove useful as a monitor for both the cardiac and the respiratory rhythms of the premature infant who is susceptible to the sudden infant death syndrome (SIDS or "crib death").

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A MICROCOMPUTER BASED NON-INVASIVE CARDIOPULMONARY MONITOR USING A MICROWAVE INTERFEROMETER

By

Tanmoy K. BASU

Thesis submitted to the Faculty of the Graduate School of the New Jersey Institute of Technology in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
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This work is a continuation of the research started by Mr. Eric Ho, an alumnus of NJIT. I express my gratitude for being able to utilize some of the computer programs developed by him.

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CHAPTER I

1.1 Introduction

The application of *microwave* energy for diagnostic purposes has not been explored much as is evident from the scarcity of published literature in that area. With a *microwave interferometer* the vibrational velocity of the anterior (front), as well as posterior (back) chest wall can be monitored and recorded. The recorded signals are a reflection of the *mechanical cardiac activity* within the chest cavity, as opposed to *electrocardiogram* (ECG) which is a reflection of the electrical cardiac activity. The *ballistocardiogram* (BCG) and the *apexcardiogram* (ACG) are two instruments which can also sense the mechanical events in the cardiac activity. In that sense therefore, our recordings from the interferometer may be expected to resemble those from the BCG and the ACG. The interferometer recordings, moreover, are obtained without touching nor disrobing the subject since microwave energy readily passes through normal dry clothing.

The recordings from an ECG are very well understood by doctors and engineers today. By studying the signals obtained from the microwave interferometer with the ECG as a timing reference, and bearing in mind that certain mechanical cardiac events, such as valves opening and closing occur at certain points in the RR interval of the ECG, an attempt has been made to identify a repetitive vibration pattern of the chest wall in normal, healthy male and female subjects. The interesting question is raised whether this technique can be used to detect those cardiac abnormalities that significantly alter the mechanical coupling of the cardiac musculature to the chest wall.

1.2 Problem Statement

A microwave interferometer that is capable of detecting the *vibrational velocity* of the surfaces of the chest cavity (anterior and posterior) has been described in detail.[1] The objective of this research work is to *monitor* and *record* with the microwave interferometer, and subsequently *analyze*, these vibrational characteristics of the chest wall of co-operative healthy, normal subjects, both males as well as females. It is ultimately the aim to evaluate the possibility of using this instrument as a *non-invasive* and *non-contacting instrument* to detect gross mechanical cardiac defects, such as large holes in the wall separating the right and left sides of the heart.

An attempt has been made to study the signals sensed by the interferometer to detect a common *'signature'* or pattern. The interferometer data from one subject is *autocorrelated* to accentuate those features that are repetitive and also to attenuate the non-repetitive features. High amplitude velocity peaks are noticed at similar times within each cardiac cycle (Refer to Figure 1.1). In order to relate the timing of the peaks in the raw interferometer signal to the timing of certain known events in the cardiac cycle, such as the R wave of the ECG (recorded simultaneously), the interferometer signal is *cross-correlated* with a pulse train obtained by filtering out the R peaks from the ECG of the same subject (Refer to Figure 8.4). With the existing knowledge of the timing of mechanical events within an RR interval, an attempt is made to relate the high-velocity peaks to these mechanical events.

1. See Chapter II, 'The Microwave Interferometer'

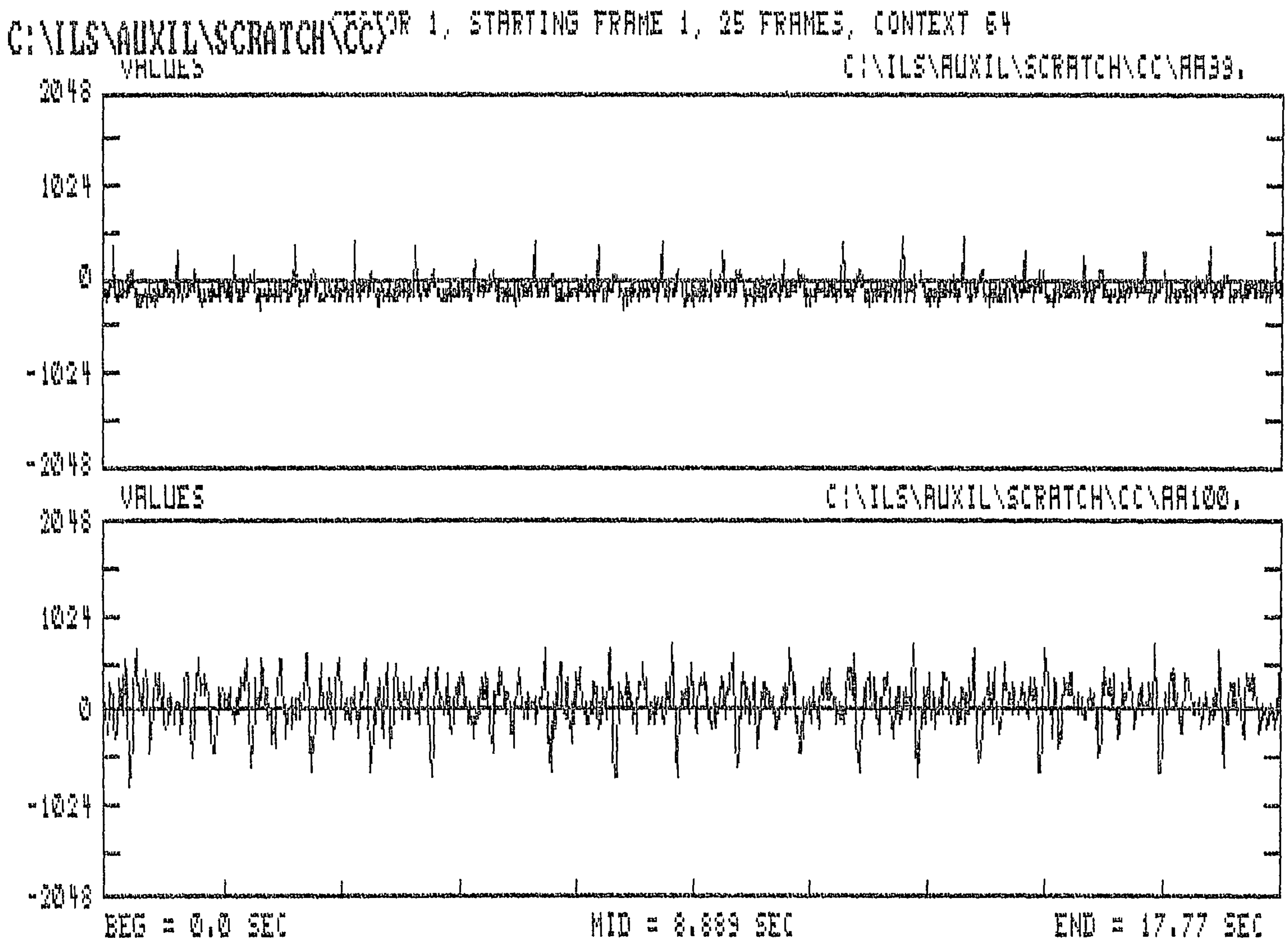

Figure 1.1 (a). Digitized ECG of a sample subject
(b). Digitized Interferometer recording of a sample subject

A description of the system hardware, the experimental set-up, and the signal processing software is discussed in detail in the following chapters.

CHAPTER II

THE MICROWAVE INTERFEROMETER

2.1 Historical Background

Early in 1964, experiments were performed at *Calspan Corporation*, Buffalo, New York, then known as *Cornell Aeronautical Laboratories* (*CAL*), to demonstrate feasibility of detecting human heartbeat with a simple ranging device. An X-band CW radar, developed at *CAL* for doppler study of water waves, was used simply because it was at hand. These preliminary experiments demonstrated that such a method of observing human cardiac function was possible, and would offer considerable potential in clinical monitoring.

During 1964 and 1965 further research was conducted at *CAL* to explore the various facets of monitoring human cardiopulmonary movements. The results of these investigations determined that a highly refined version of the radar that was used for experimentation would be required to yield any further improvements in such observations.

The *microwave interferometer* used in the experiments described in this thesis was custom designed and built in 1966 at *CAL*. This instrument was developed to monitor the vibrations of the anterior wall of the chest cavity, resulting from cardiac activity. The information content of the signals recorded by this instrument is expected to resemble those derived by a *Ballistocardiogram* or an *Apexcardiogram*.

2.2 WORKING PRINCIPLE OF THE MICROWAVE INTERFEROMETER

The basic working principle of the *microwave interferometer* is to illuminate the chest wall with a *low intensity*, *highly coherent microwave beam*, and then compare the *phase* of the *incident wave* with that of the *reflected wave* that is *modulated* by the movement of the chest wall, in response to the *mechanical events* in the cardiac activity. When the subject's chest moves, the phase relationship between the transmitted and the reflected wave is detected, and this measure of phase difference is used as raw data and analyzed using a computer to extract information about the cardiac cycle.

2.3 ELECTRICAL AND MECHANICAL DESCRIPTION OF THE MICROWAVE INTERFEROMETER.

The microwave interferometer used in conducting this research weighs about 350 Lbs. and has approximate dimensions of 300cm height, and 65cms in width and depth. It is mounted on wheels to give it mobility. The microwave circuit is mounted on one chassis and is connected by a cable to a relay rack enclosure that makes up the control cabinet.

Coherent electromagnetic energy generated by a *low-power reflex-klystron oscillator*, operating at a frequency of 9.3GHz., corresponding to a free-space wavelength of 3.1cm, is radiated from a transmitting horn antenna to illuminate the subject's chest.[1] The energy reflected from the chest wall is collected in a receiving horn antenna and sent to the receiving circuitry where the phase of the received wave is

1. A microwave oven operates at 2.45GHz at a wavelength of 12.2cm.

compared with the phase of the incident wave. The phase of the reflected energy is modulated by the motion of the chest wall; hence the phase difference between the coherent incident energy and the time-modulated reflected energy reflects the motion of the chest wall. A block diagram of the microwave interferometer is shown in Figure (2.1).

The interferometer may be most briefly described as a *phase-locked*, *coherent*, *low-power radar*. The operation of this instrument can be described as follows: a *reflex-klystron oscillator generates microwave energy* at a nominal frequency of 9.3GHz. Most of this energy is passed through a 60Hz balanced modulator, and a single sideband filter to the receiver, where it is introduced as a local oscillator input to the receiver mixer.

The remaining fraction of the klystron power is sampled by the 30dB directional coupler and is passed through the *Travelling Wave Tube* (*TWT*) which functions as both a phase shifter and an amplifier. The energy is then transmitted through a microwave horn antenna to its target. The coherent energy reflected from the target, i.e. the subject's chest wall, is shifted in phase by an amount directly proportional to the distance range between the transmitter and the target; as the target vibrates, the phase of the reflected wave vibrates proportionally.

The microwave receiver mixes the local oscillator signal and the received signal, to produce a 60MHz phase modulated intermediate-frequency (IF) output. This receiver IF output contains the phase shift information derived from the reflected microwave energy, and is amplified by a commercial FM receiver. The output of the FM receiver is further reduced in frequency to a 10.7MHz signal containing the phase shift information.

A sample of the 60MHz crystal oscillator signal used to drive the balanced modulator is passed through a similar FM receiver, which has an output of 10.7MHz but contains no target phase shift and is the reference signal. The two 10.7MHz signals are separately amplified and applied to the grids of a phase detector tube.

The output of the phase detector is a voltage whose amplitude is proportional to the amount of phase shift contained in the signal derived from the microwave receiver. This output voltage is amplified and applied directly to the TWT phase shifter in the transmitting arm of the microwave interferometer system. This closes the *electronic loop* and the system has become a *phase-locked radar.* The action of the phase-lock loop is such that it maintains a specified phase shift as detected at the microwave receiver. Thus when the reflecting target moves, the phase-lock loop instantly corrects for the phase shift by *electronically* moving the entire radar. This corrective action is not accomplished by any mechanical movement, but electronically by the phase shift capability of the *Travelling-Wave Tube* (*TWT*). Approximately 1000^{o} of phase shift can be effected by the *TWT* over an applied helix voltage range of 250Volts DC. The corrective feedback voltage applied to the *TWT* is our output signal from the interferometer representing the overall chest wall motion. This signal contains the chest vibrations caused by the mechanical events in the cardiac cycle as well as low frequency, high amplitude component contributed by breathing. To obtain the contribution of the cardiac cycle alone, the signal is *hi-pass* filtered. Since *hi-pass* filtering is an action equivalent to *differentiation*, the final signal that we acquire from the interferometer is a measure of the *velocity of vibration* of the chest wall.

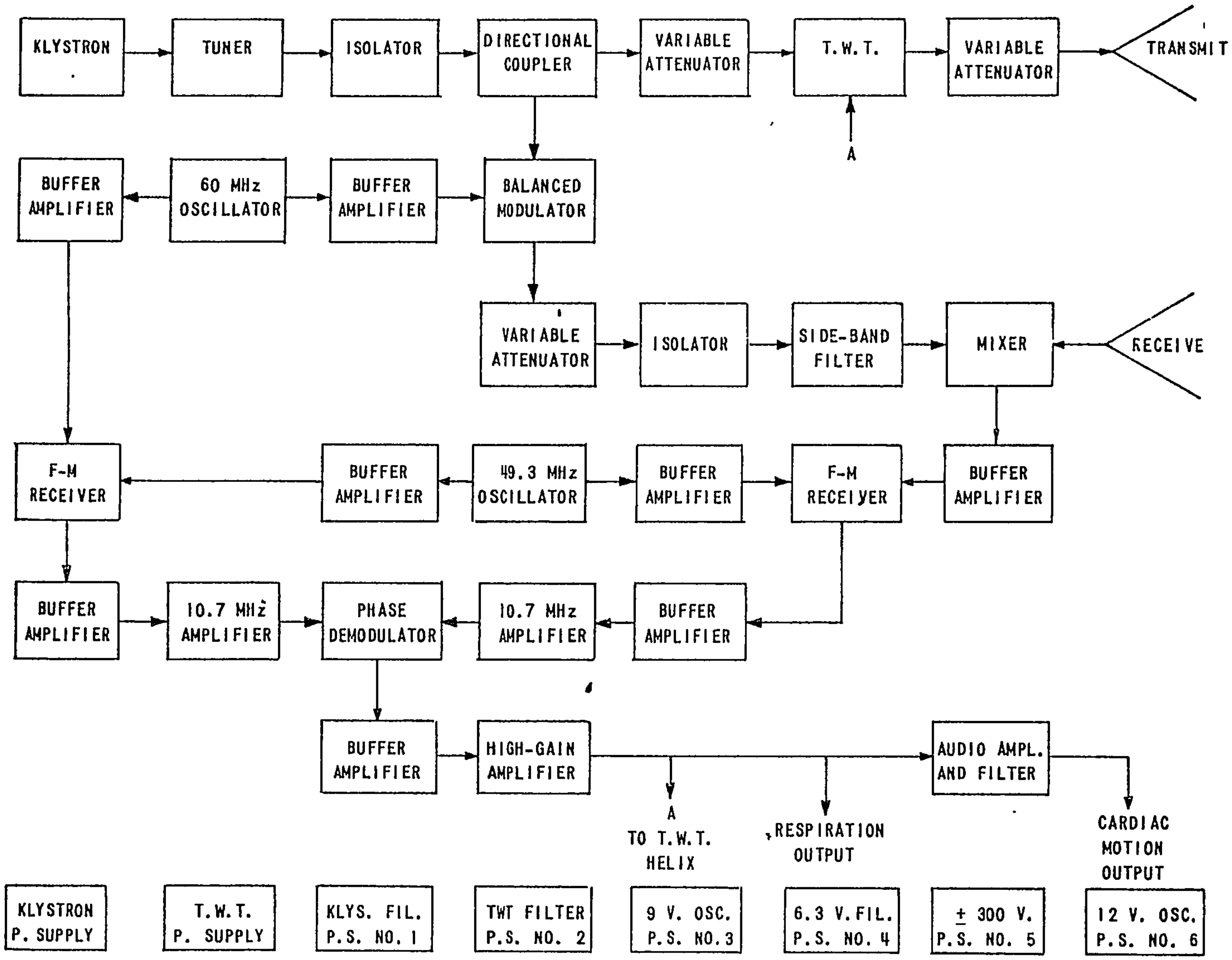

Figure 2.1 A block diagram of the Microwave Interferometer

The *Travelling-Wave Tube* (*TWT*) contains a DC-biased helix through the center of which an electron beam is passed. Microwave signals coupled to one end of the helix produce a relatively slow moving electromagnetic wave that interacts with the electron beam. The electron beam yields energy to the electromagnetic beam in its passage through the helix. This results in an amplified signal at the end of the helix. The TWT serves as an amplifier over a broad band of frequencies as well as a phase shifter for any specified microwave frequency that falls into its range of operation. Since wide bandwidth is not a requirement, the *TWT* that is used in this instrument is for a specified frequency, with all other characteristics adjusted for optimum operation as a phase shifter.

The resolution of the interferometer has been estimated to be about 1/100th of a degree of carrier phase shift. This resolution corresponds to a target displacement of less than one micron. The vibration of the chest wall resulting from mechanical cardiac activity is therefore readily detected as, of course, are the much larger chest-wall displacements at a lower frequency caused by breathing.

The electromagnetic energy to which a subject is exposed during approximately two minutes of data collection is minimal. Using a very sensitive and calibrated Electromagnetic Radiation Monitor (NARDA Model 8316B), the patient exposure was determined to be less than 0.02mWatts/cm^2. The energy leaking from a microwave oven was measured to be 25 times larger at 0.5mWatts/cm^2.[2]

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2. Maximum allowable leakage from a new microwave oven is known to be 1mWatts/cm^2.

CHAPTER III

AN OVERVIEW OF THE EXPERIMENTAL SET-UP

3.1 SYSTEM DESCRIPTION

The schematic diagram of the system which has been designed and developed to sense, monitor, record and analyze the vibrational velocities of the human chest wall, caused by mechanical cardiac activity, is shown in Figure **(3.1)**. It can be further divided into the following subsystems:

1. The microwave interferometer and the ECG recorder.
2. The analog filter.
3. The IBM/AT personal computer and DASH-16 A/D-D/A converter board with ILS-IEEE signal processing software.

All subjects are required to lie down on a table with the microwave radiation illuminating their *anterior* (or *posterior*) chest wall. Three ECG electrodes are also attached to the subjects. The subjects were each required to sign a *consent* form, a copy of which is enclosed in Appendix (C).

3.2 OPERATIONAL SET-UP OF THE MICROWAVE INTERFEROMETER

The main power supply switch of the interferometer is turned on and the instrument is allowed to warm up for about 5 minutes. Following this, the High Voltage (HV) switch in the *Travelling-Wave Tube* section and the power supply

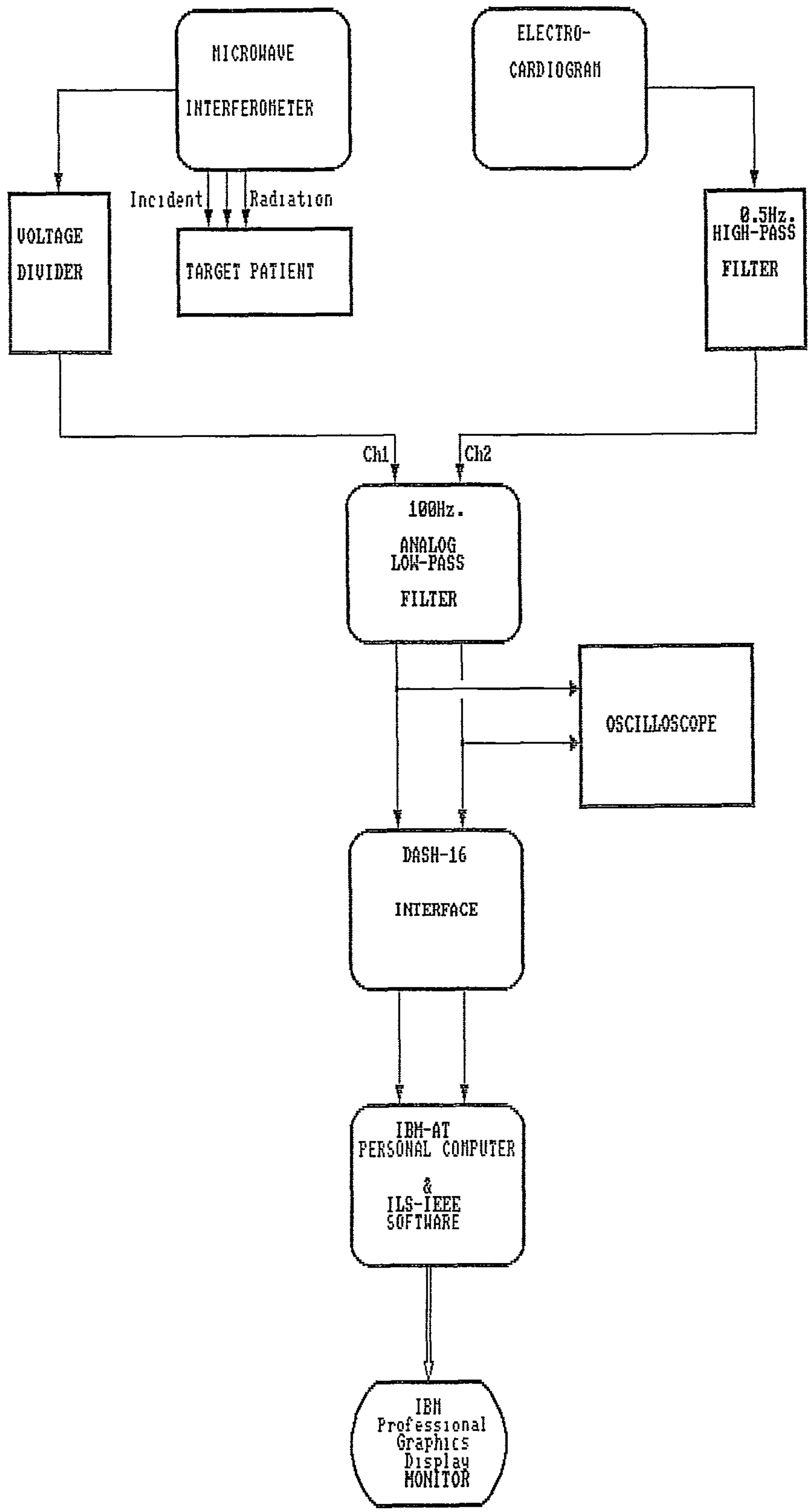

Figure 3.1 A block diagram of the Microwave interferometer based Cardiopulmonary Monitoring system

switch to the klystron section are turned on. The various operating values (at 9.3GHZ) for currents and voltages in the different sections are as listed below:

Klystron Section:

Reflector Voltage approx.= 40V

Beam Voltage approx = 275V

Beam Current approx = 16mA

The CW switch on the klystron power supply is turned on only after the subject is comfortably positioned and breathing normally.

Travelling-Wave Tube Section:

Beam Voltage = 2066V

Cathode Current approx = 17.5mA

The ammeter indicating the current in the Balanced Modulator should display 0.9mA and the Receiver Crystal Current indicator should display approximately 28microA.

The output of the interferometer is connected to an oscilloscope and is also applied as an input to one of the channels of the 100Hz low-pass Butterworth Filter (manufactured by Rockland Systems Corporation, Model 1024F).

3.3 ELECTROCARDIOGRAM SET-UP

The ECG recorder is turned on and the gain is adjusted. ECG electrodes from the patient cable are attached to the subject's right and left arm and the third lead (ground) is held by the subject between the index finger and the thumb of the right arm. The signal obtained from the ECG is often prone to *baseline drifting*. To avoid this drift, the signal from the output of the ECG machine is filtered using a 0.5Hz. *high-pass analog filter*. The high-pass filtered signal is fed as input to the second analog channel of the 100Hz low-pass filter.

3.4 COMPUTER HARDWARE

The IBM-AT personal computer used as a part of this system is equipped with special modular software and hardware for easy interfacing with laboratory instruments and systems. It is particularly well suited for slow data acquisition and is capable of fairly sophisticated data processing. The hardware used for this research work are:

1. IBM-AT personal computer with 16-bit 80286 processor. The system has 640 Kilobytes of on board memory using 64K RAM chips.
2. A Winchester type hard disk system with 20 Megabytes of storage.
3. A single 5-1/4 inch size floppy disk drive formatted for a capacity of 360 Kilobytes.
4. A color graphic display unit with monochrome and parallel printer adapter.
5. A dot-matrix graphics printer with a moving head. (TEC Tokyo Electronic Co., Model 8510).
6. DOS 3.1 operating system.

3.5 EXPERIMENTAL SESSION

The signals from the interferometer and the ECG, which are recorded simultaneously, after suitable analog filtering as described above, are then applied to the first two channels of the DASH-16 A/D-D/A converter for digitization. Data are taken for approximately one minute for each subject, and the acquisition procedure, as described in the following section is done by invoking a program called *DATAACQ.BAS* written in GWBASIC. The two channels of digitized data are stored on the hard-disk of the personal computer, and subsequently processed using ILS software as described in the section[3] discussing signal processing. The processed signals are then graphically printed out as plots on a dot matrix printer.

3. See Chapter VII(Section 7.2)

CHAPTER IV
SYSTEM SOFTWARE FOR DATA PROCESSING

4.1 DATA ACQUISITION AND ANALOG TO DIGITAL CONVERSION

The 100 Hertz analog filtered signals are digitized using DASH-16, a 12 bit data acquisition and control interface board (manufactured by Metrabyte Corporation, Stoughton, MA.)[4], which is installed on an IBM-AT personal computer. Channel *ZERO* and Channel *ONE* of the eight channels in the bipolar mode of the DASH-16 are used in the analog to digital conversion. A BASIC program called *DATAACQ.BAS*[5] has been developed for data acquisition. With the patient lying down, relaxed and breathing normally, the signals from the interferometer and the ECG recorder are digitized and stored by DATAACQ.BAS in a file called HO10, directly on the 20 Megabyte hard disk of the personal computer.

The *DATAACQ.BAS* program is run by typing "GWBASIC" at the default directory which must contain the following files:

1. DASH16.BIN
2. DASH16.OBJ
3. DASH16.ADR

At the GWBASIC prompt "OK" type "LOAD DATAACQ.BAS" and key ENTER. Once the program is loaded and the system flashes an "OK" prompt, type "RUN" and key ENTER. The program execution begins and certain messages appear on the screen. In response to the message:

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4. See Appendix (B) for details on DASH-16.
5. See Appendix (A-2) for listing of DATAACQ.BAS.

" Lower multiplexer scanning limit (0-7 or 15)? : "

type '0' and key ENTER.

In response to the next message:

" Upper multiplexer scanning limit (0-7 or 15)? : "

type '1' and key ENTER.

The program now samples each channel at a sampling frequency of 150Hz for 9,000 points each. As per sampling theorem, data ought to be sampled at a sampling frequency that is at least twice the useful frequency component of the signal. In our case the sampling frequency should be 200Hz or more since the signal was low-pass filtered at 100Hz. Due to an oversight however, data has been sampled at 150Hz and we may safely assume the interferometer signal does not have any useful content between 75Hz and 100Hz. After 59 seconds the data block has been sampled and the program will prompt with the following message:

" (1) Show the input signal. "

" (2) Show the input signal and save it in file HO10. "

" (3) Save the data in file HO10. "

Type '2' or '3' as desired. The file HO10 now contains two channels of digitized data stored alternately (CH1, CH2, CH1, CH2, ----- and so on).

Following this step exit from GWBASIC by typing "SYSTEM" to the "OK" prompt.

4.2 DATA SEPARATION

The two channels of raw data from the interferometer and the ECG, as obtained by DATAACQ.BAS, are stored in the single file HO10. The two channels need to be separated so as to perform meaningful signal processing. This task is achieved by executing a program called TANMOY.EXE[6], which is written in the high level language C. This program is executed by entering the following in response to the C:\ prompt.

" TANMOY IN_FILE OUT_FILE_1 OUT_FILE_2 "

where,

IN_FILE is the input file created by DATAACQ.BAS.

OUT_FILE_1 is the output file name of channel 1 (interferometer) data.

OUT_FILE_2 is the output file name of channel 2 (ECG) data.

Both OUT_FILE_1 and OUT_FILE_2 are files in ASCII code.

Example: " TANMOY HO10 CH_1.DAT CH_2.DAT "

On typing the above line and keying ENTER the message

" Start .... Please Wait "

will flash on the screen. After successful execution of the program, all the data have been separated, and the computer will indicate so by the following prompt :

" Original data file = HO10 has 20,0000 data points"
" Channel 1 data file = CH_1.DAT has 10,000 data points"
" Channel 2 data file = CH_2.DAT has 10,0000 data points

i.e. the program TANMOY.EXE took HO10 as its input and separated the two channels of data and placed them in the two output files CH_1.DAT and CH_2.DAT.

The data acquisition and data file separation protocols are now complete.

4.3 DATA FILE CONVERSION

The ILS-IEEE signal processing software used in this research work is a low cost learner's version. It does not support A/D-D/A operations by the user; processing is limited to signals generated by ILS itself or supplied with the package. To

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6. See Appendix (A-3) for source code.

overcome this limitation a program called CONVERT.EXE[5] has been developed in C language. CONVERT.EXE can translate the data file obtained as output of TANMOY.EXE in ASCII code into ILS acceptable code in the sampled-data[8] file. CONVERT.EXE can be run by typing the following:

" CONVERT IN_DATA_FILE HEADER_FILE OUT_DATA_FILE "

where,

IN_DATA_FILE is the file name of the first output data file
from TANMOY.EXE

HEADER_FILE is the file name created by ILS

OUT_DATA_FILE is the name of the translated data file which is ILS acceptable.

Examples: CONVERT CH_1.DAT HEADF TB100

CONVERT CH_2.DAT HEADF TB101

Running this program will request response to :

" Default data points transferred are : 15,000 "
" Do you want to change the number ? "
" Type 'Y' to confirm OR RETURN for default "

Normally, the number of data points to be converted are more than 15,000. Therefore type 'Y' and respond to :

"!!!!!!! Input Bytes Number == ? " by entering "20,000"

Within a moment data conversion takes place and the display " 20,000 Bytes Translated " comes on screen.

4.4 'R' PEAK DETECTION FROM THE ECG

5. See Appendix (A-5) for source code.
8. Refer to Chapter VII, Section 7.1.1

In order to be able to study the interferometer data with the ECG as a timing reference it was felt necessary to detect the R peaks in the ECG taken from each subject. A very simplistic approach has been adopted to achieve this end. One of the outputs of TANMOY.EXE is a file containing the ECG data in terms of ASCII code (i.e. numeric values representing the amplitude values of the ECG corresponding to the time axis points). This file can be easily read using any editor[9] and the R peaks can be easily identified which show up as distinctly large positive integers. By sampling this data manually a threshold value is selected. A program called BASU1.PAS[10] has been developed in Pascal which does the following:

1. Reads the ASCII file containing the ECG data.

2. Compares each data value read with the given threshold value.

3. If the data value read is less than the threshold, it outputs a zero value. If the value is greater than or equal to the threshold, it outputs the read value.

In this way, the output is a long string of zeroes with some positive integers located at the points of occurrence of the R peaks in the original ECG. To obtain a train of pulses representing the R peaks with uniform amplitude and pulse-width we further edit the output file of BASU1.PAS. For example for a threshold value given to BASU1.PAS, if a section of our output is of the form:

...,0,0,0,0,0,34,0,0,0,0,0,0,0,35,0,0,0,0,0,0,37,0,0,0,0,0,0, ...

we would modify it to the form:

...,0,0,0,40,40,40,0,0,0,0,0,0,40,40,40,0,0,0,0,0,40,40,40,0,0,0,....

This would result in a pulse train of equal amplitude representing the R peaks with each pulse having an amplitude value 40 and width of three points on the time axis.

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9. In this case the TURBO PASCAL Editor has been used
10. See Appendix (A-4) for source code.

The ECG pulse train thus obtained is next converted to ILS acceptable data by executing CONVERT.EXE as explained above.

At this stage we have the following three sets of data files, all in ILS acceptable forms:

1. The raw ECG data (in a file with the general name XX99[11])

2. The raw microwave interferometer data (in a file with the general name XX100)

3. The R-peak detected ECG pulse train (in a file with the general name XX101)

where XX stands for the name initials of each subject.

These signals are processed using ILS IEEE as explained in Chapter VII of this thesis.

11.Refer to ILS-IEEE manual about file naming.

CHAPTER V

CARDIOVASCULAR DYNAMICS

5.1 MECHANICAL EVENTS OF THE CARDIAC CYCLE

5.1.1 INTRODUCTION

Electrical events in the heart trigger the mechanical events. By considering a conventional cardiogram as a timing reference, it is possible to deduce what mechanical events take place during the various phases of the cardiac cycle. The waves in a conventional electrocardiogram are the voltages generated by the heart as recorded by the surface electrodes. In other words waves of electrical *depolarization* and *repolarization* that trigger the cardiac muscle cells to contract and relax rythymically results in the ECG. An *action potential* is a potential difference created across a cell membrane when it is excited by the flow of ionic currents or by some form of externally applied stimulus. The cause of this stimulus is the imbalance of potassium ions within a cell caused by the inrush of sodium ions into the cell, when the cell is excited. A cell that has been excited and displays an *action potential* is said to be in a state of *depolarization*. As each cell must return to its *resting membrane potential*, the sodium pump actively transports sodium ions back to the outside of the cell. This process by which a cell is *polarized* back to its normal resting potential is known as *repolarization*.

The various mechanical events will be described in sequence --that is , we will describe the changes in all variables in one phase of the cycle, then discuss the next portion of the cycle, etc. In this discussion, an attempt will be made to discuss the mechanical changes which are of primary concern to us.

In a healthy heart the atria and the ventricles are separated by valves (*mitral* in the left heart and *tricuspid* in the right); when the valves are open, the pressure pulse in the two chambers will be similar with a small pressure gradient in the direction of flow. The phases of contraction (*systole*) and relaxation (*diastole*) are named in a fashion which describes the activity of the atria and the ventricles. Figure (5.1) shows the events of the cardiac cycle; the vertical lines mark the beginning of the successive phases.

5.1.2 DIASTASIS

As depicted in Figure (5.1), the cycle begins at the end of diastole. The pressure in the aorta is falling, owing due to the '*runoff*' of blood into the peripheral vessels. Volume and pressure in the atria and ventricles are rising slightly since the venous pressure exceeds the pressure within the chambers. The atrioventricular valves have long been open. No potentials are recorded in the electrocardiogram, and no sounds are heard stethoscopically. The diastolic period extending from the end of the rapid filling phase in one cycle to the atrial contraction in the next cycle is known as the period of *diastasis*. *Diastasis* is of variable duration and depends on the heart rate. The P wave of the electrocardiogram occurs at the end of this phase.

5.1.3 ATRIAL CONTRACTION

Slightly after the beginning of the P wave, which is a wave of electrical *depolarization* that *stimulates* the atria, (during the diastolic period) the atria commence their contraction . This contraction leads to a surprisingly slight rise in the intra-atrial pressure (the pressure change is only about 5mm Hg). With atrial contraction, the ventricular volume and pressure increase slightly owing to the atrial ejection of blood (ventricular pressure increases by about 3mm of Hg). The major portion of ventricular filling occurs during the period of diastasis (see

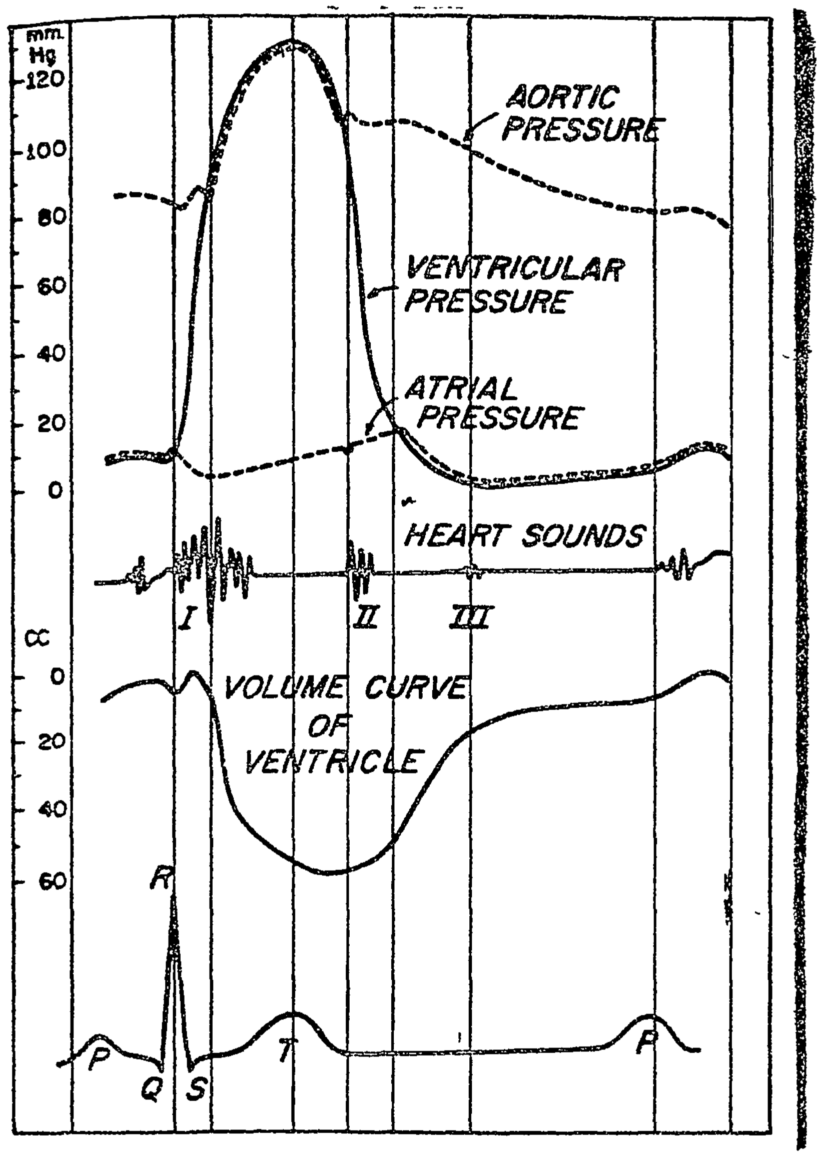


Figure 5.1 Events of the cardiac cycle. This diagram consists of five labeled curves plus the electrocardiogram (lowest curve). The various phase of the cardiac cycle are separated by vertical lines. (From Wiggers, Circulatory Dynamics. New York, Grune and Stratton)

discussion below on period of rapid filling). Atrial contraction has generally been considered as a relatively trivial contributor to the filling of the ventricles. It now appears that, if the heart rate is slow enough so that there is a true period of diastasis, atrial contraction produces a rise in ventricular pressure and the A-V valves often close because of atrial ejection , so that this rise in pressure is maintained. If the heart rate is rapid, ventricular pressure records show no clear atrial component. During this time, the pressure in the aorta continues to decrease as blood flows into the arterioles. A very faint atrial vibration, not normally perceived as a sound, occurs at this time. The ventricles begin to depolarize during this period, as shown by the beginning of the QRS complex. The atrial pressure wave lasts about 0.1 second.

5.1.4 VENTRICULAR ISOMETRIC (ISOVOLUMETRIC) CONTRACTION

The next event is the onset of ventricular contraction. It begins shortly after the onset of the ventricular electrocardiographic complex (QRS) which is the electrical depolarization of the ventricular muscles and the repolarization of the atrial muscles. The first period of ventricular contraction is called the 'isometric phase'. At the beginning of ventricular contraction, the atrio-ventricular valves (A-V valves, viz. mitral and tricuspid) may be open or closed. If they are open, as the interventricular pressure rises and exceeds the atrial pressure, the valves close. The aortic and pulmonary valves are, of course, also closed. Since blood is an incompressible fluid, this is by definition an 'isovolumetric', or 'isometric' phase of contraction ; i.e., the volume of blood in the ventricles is constant.

At the beginning of ventricular contraction, the aortic pressure is about 80 mm. Hg, the pulmonary pressure is about 7 mm. Hg, and ventricular pressure is only slightly above atmospheric pressure. The ventricles change dimensions as the muscle fibers contract, but no blood is ejected into the arteries and none flows retrograde into the atria once the valves are closed. Pressure in the arteries and the atria are thus not directly affected even though ventricular pressure rises steeply; both pressure and muscle fibre length change. During this phase, several investigators[2,3] have observed a slight increase in apparent ventricular volume despite the fact that inflow and outflow valves are closed. When the diameter or circumference of the ventricle is measured during this period, a change in shape is observed in the ventricular volume recording.

5.1.5 RAPID EJECTION

When the pressure in the left ventricle first exceeds the pressure in the aorta, the aortic valve opens. Since there is now a large orifice between the aorta and the ventricle, the two form virtually a single chamber; pressure curves measured in the two regions follow one another closely as seen in Figure 5.1. Blood flows rapidly from the ventricle into the aorta. During this period of maximum ejection, the ventricular volume decreases sharply. Years of extensive research on ventricular volume, pressure and aortic flow curves indicate that aortic flow reaches its peak velocity in about 0.10 second, whereas pressure reaches its maximum in about 0.18 second after the onset of rapid ejection. The aortic flow curve is very asymmetrical, with rapid initial ejection followed by a slower return to zero. By the time pressure reaches its peak, flow may have declined to two-thirds or one-half of its maximum value. Atrial pressure even falls below venous pressure, and the atria begin filling at this time. At the end of the period of maximal ejection, the beginning of ventricular repolarization is signaled by the onset of the T wave which represents ventricular repolarization.

As indicated, the period of increasing rate of flow(i.e., positively accelerating flow) is short. Although flow from ventricle to the aorta continues, the velocity decreases. Rate of change of velocity is negative. While the flow velocity is decreasing, the aortic pressure is slightly higher than the ventricular pressure[1]. On the average, ventricular pressure exceeds aortic pressure only during the initial 45 per cent of the ejection phase.

5.1.6 DECREASED EJECTION

Following the initial period of rapid ejection, the rate of flow from the ventricle decreases markedly and there is a period of reduced ejection. The ventricular volume curve starts to level off, and the ventricular and aortic pressures begin to fall. The ventricles appear to exert their maximum effort during the initial phase of ejection. It is also possible that there is some influence of the end of depolarization. The venous pressure continues to be greater than atrial pressure; the atria continue to fill. Electrically this period is marked by the major deflection of the T wave; i.e., ventricular repolarization becomes complete.

5.1.7 PHASE OF ISOMETRIC (ISOVOLUMETRIC) RELAXATION

When the ventricular ejection per unit time falls to zero, the left ventricular pressure falls below the pressures in the aorta and pulmonary artery. The aortic

1. Spencer, M.P. and Greiss, F.C., Circulatory Res.,1962

and pulmonary artery valves therefore close. The ventricular pressure continues to fall rapidly as the ventricles relax. The A-V valves remain closed as long as the ventricular pressure exceeds atrial pressure. This is the period of isometric relaxation. Because the valves at both ends of the ventricles are closed, the amount of fluid contained in the ventricles obviously cannot change except for small amounts of blood flowing into the right heart from coronary veins. The term 'isovolumetric relaxation' appropriately describes this phase of the cardiac cycle.

5.1.8 PHASE OF RAPID VENTRICULAR FILLING

The isometric relaxation phase ends when the ventricular pressure falls below the pressure in the atria; the A-V valves the open, and a phase of rapid ventricular filling begins. It should be noted that, during all this period, flow of blood from the aorta to the peripheral arteries continues and the aortic pressure falls slowly. It has been claimed that ventricular diastolic suction contributes to the ventricular filling. Apparently the ventricle is able to do the work of filling itself with blood, i.e., the fact that the ventricle is empty but relaxed makes the atrioventricular pressure difference greater than the difference between the atrial and intrathoracic pressures. If *suction* is important in the normal heart, it is during this period of rapid filling.

The phase of rapid inflow is followed by a phase of diastasis during which filling is much less rapid. Filling is limited, too, because the ventricle has come close to a maximum diastolic size, which, for a given cycle length is determined by the atrial pressure (although it may be changed by nervous, hormonal and other factors). This period of diastasis ends the cycle and is terminated by atrial systole, which begins the next cycle. Pressure changes in the human heart have been recorded during cardiac surgery. In general the results are similar to those previously described. Right atrial contraction precedes left atrial contraction by about 20 milliseconds. Right ventricular ejection also begins slightly earlier than does ejection from the left ventricle. Furthermore, mitral valve closure follows tricuspid closure and the pulmonic valve open before, and closes after, the aortic valve.

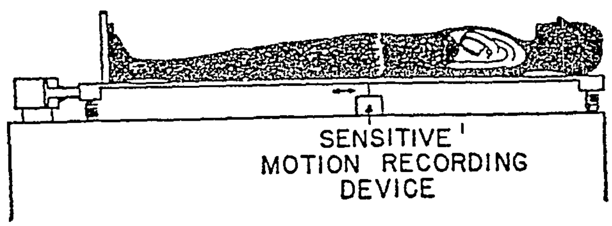
5.2 TRADITIONAL METHODS OF MONITORING MECHANICAL EVENTS OF THE CARDIAC CYCLE

5.2.1 The Ballistocardiogram (BCG)

Ballistocardiography has been attempted for computing values presumed to represent stroke volume or cardiac output. Blood ejected from the two ventricles moves simultaneously in several directions after leaving the heart. Its energy is imparted to the body at every turn. A general method of Ballistocardiography is shown in Figure (5.2 a). A low frequency spring mounted table is used for Ballistocardiography because the body cannot be rigidly fastened to the table. The tissue in contact with the table have an elasticity which is equivalent to interposing a spring between the body and the table top.

Ballistocardiography records consist of a series of deflections which are related to the events of the cardiac cycle. Although the forces developed by the heart and blood affect the recorded patterns, a consistent relationship between these deflections and stroke volume is probably most fortuitous for the most part.

BALLISTOCARDIOGRAPH



BALLISTOCARDIOGRAM

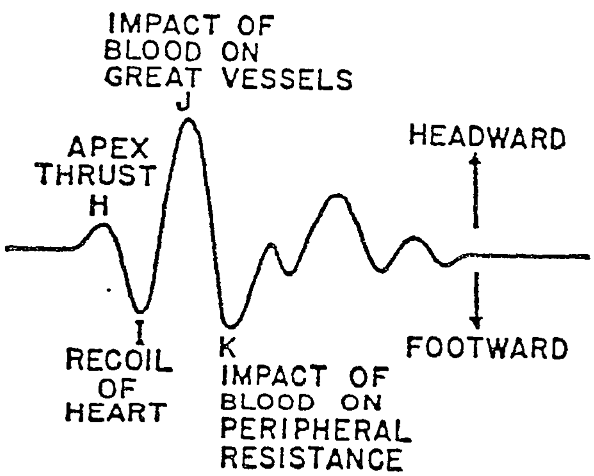


Figure 5.2 (a). Ballistocardiograph
(b). Ballistocardiogram
(Reproduced from Rushmer, CARDIOVASCULAR DYNAMICS)

Using a simple, low-frequency Ballistocardiograph, it has been demonstrated that the mass of the body itself renders the Ballistocardiograph an imperfect recorder of oscillations. The recorded oscillations are the result of vascular and body movements, as these may be in phase and reinforce one another, or be out of phase and cancel each other. Reconstruction of the Ballistocardiographic records led to the following description of the cause of the various oscillations, as shown in Figure (5.2b).[2]

The H wave begins with the movements that take place during isometric contraction of the heart and are the most variable. The I wave is the result of a partially cancelled footward thrust that is developed as blood is ejected from the heart into the ascending aorta and the pulmonary artery. The J wave has a complex origin, including the deceleration of blood in the heart, the ascending aorta and the pulmonary artery, and the acceleration of blood in the descending aorta.

The I and J waves are related to the cardiac output and the shape of the ballistic curve is determined by the blood-velocity-time profile in the great vessels.

5.2.2 The Apexcardiogram (ACG)

The technique used to record the precordial movements of the front surfaces of the chest, is known as Apexcardiography, and the record is referred to as the Apexcardiogram (ACG). This vibration is produced by the mechanical coupling of the heart to the front (anterior) wall of the chest cavity. In the last twenty years the ACG has been used primarily for diagnostic purposes. The ACG represents the

2. From Rushmer, Cardiovascular Dynamics, Second edition.

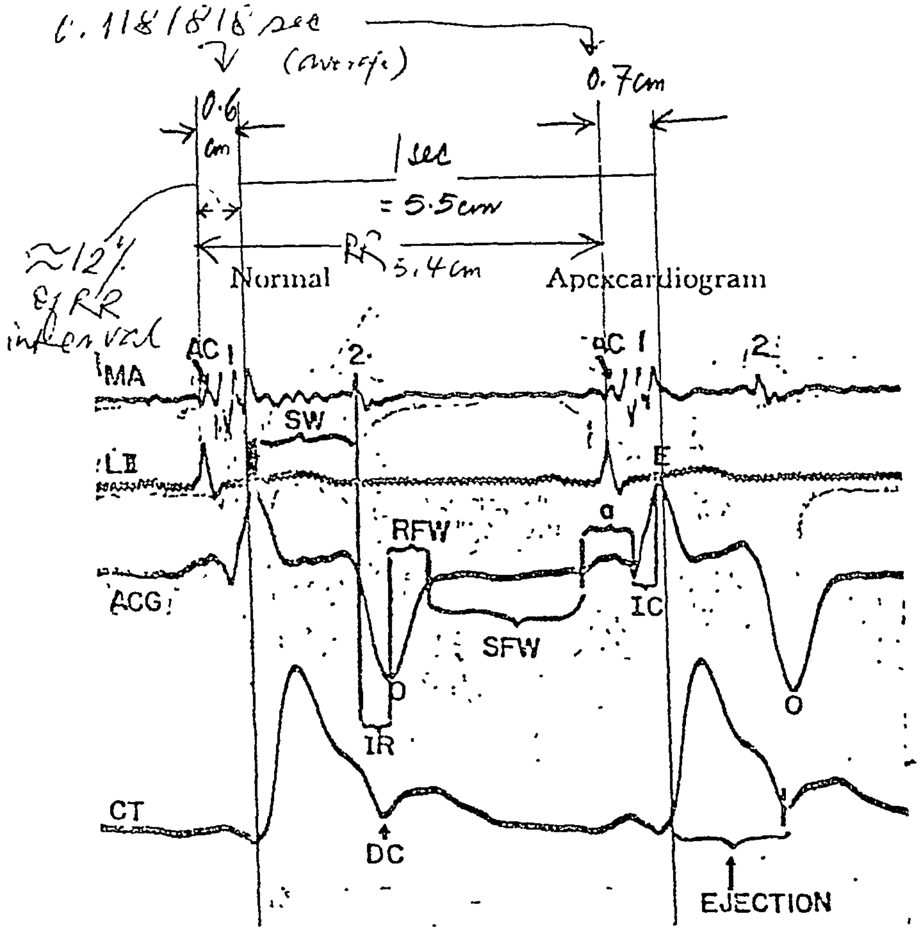
low frequency displacement curves of the precordium overlying the apex of the heart regardless of the position at the chest wall, and has been correlated with hemodynamic events within the left ventricle.

In the system used to record the ACG, either a displacement (linear) or velocity (gradient) microphone is used to convert the mechanical movement of the chest wall into electrical signals. The subject is placed on his left side, and the point of maximal cardiac impulse (apex beat) is determined by palpation. The pick-up bell of the microphone is placed directly over the apex beat and the instrument is held in position by hand with slight to moderate pressure applied to the chest wall. The tracings are recorded while the subject is holding his breath at the end of expiration or at the beginning of inspiration.

Figure (5.3) shows the ACG in a normal subject recorded simultaneously with the phonocardiogram (MA), the ECG (L_{II}) and carotid pressure tracing (CT). The identification of the different components of the ACG is based on simultaneous recording of intracardiac pressure curves, the ECG, and the phonocardiogram in normal subjects and in patients with heart disease.

A normal ACG is characterized by the following deflections:

1. The 'a' wave: This results from ventricular filling due to atrial contraction. This wave occurs 0.08 to 0.12 seconds after the beginning of the ECG P wave and coincides with, or shortly precedes, the QRS complex in the ECG. It coincides with the fourth heart sound or with the atrial component of the first sound in the phonocardiogram.



Apexcardiogram in a normal subject recorded simultaneously with the phonocardiogram (MA), the electrocardiogram (L II) and carotid tracing (CT). Note the small *a* wave preceding the QRS complex of the electrocardiogram and coincident with the atrial component of the first heart sound (AC). The E point coincides with the beginning of the systole of the carotid tracing (CT). The O point follows the dicrotic notch of the carotid tracing by 0.03 sec. The peak of the rapid-filling wave is coincident with a low amplitude third heart sound. IC = isometric contraction. IR = isometric relaxation. SFW = slow-filling wave. RFW = rapid-filling wave. Time lines = 1 sec.

Figure 5.3 Apexcardiogram (Reproduced from American Journal of Cardiology, Vol. 8, P.368, 1963)

2. E point isometric contraction: After the a wave has been inscribed, the tracing presents a rapid rise reaching a sharp peak at the instant of the opening of the aortic valve. This sharp peak is designated the E point since it appears to mark the beginning of ventricular ejection.

3. Systolic wave: This is due to ventricular contraction. It has a 'tent' shape. It begins with the E point and ends with the O point.

4. Isometric relaxation: The beginning of this phase is not well defined in the ACG. Its end is represented by the O point.

5. Rapid-filling wave (rapid ventricular filling): This phase of the cardiac cycle is represented in the ACG by a rapid, upward deflection which begins with the O point and ends with a sharp peak, which is distinctly separated from the next slow-filling wave.

6. Slow-filling wave: This wave represents the slow ventricular filling phase.

CHAPTER VI

THEORY OF GENERALIZED HARMONIC ANALYSIS

6.1 CORRELATION

In the general theory of harmonic analysis, an expression of considerable importance and interest is, in the case of periodic functions,

$$1/T_1 \int_{-T_1/2}^{T_1/2} f_1(t)\, f_2(t+\tau)\, dt \qquad (6.1)$$

where $f_1(t)$ and $f_2(t)$ have the same fundamental angular frequency w_1 and τ is a continuous time of displacement in the range $(-\infty, \infty)$, independent of t. One important property of this expression is the that it can be shown that its Fourier transform is

$$\bar{F}_1(n)F_2(n) \qquad (6.2)$$

if $f_1(t)$ has the complex spectrum $F_1(n)$, and $f_2(t)$, $F_2(n)$. The bar indicates the complex conjugate of the quantity over which it is placed. We shall call this relation the correlation theorem for periodic functions.

The integral in equation (A) involves a combination of three important operations:

1. One of the periodic functions concerned, $f_2(t)$, is given a time displacement τ.
2. The displaced function is multiplied by the other periodic function of the same fundamental frequency.
3. The product is averaged by integration over a complete period.

These steps are repeated for every value of τ in the interval $(-\infty, \infty)$ so that a function of τ is generated. This combination of the three operations, namely, displacement, multiplication, and integration, is termed correlation. Correlation is not limited to periodic functions, as indeed it is applicable to aperiodic and random functions.

6.2 AUTOCORRELATION

In the correlation theorem for periodic functions (equation 6.1), if under a special condition we have $f_1(t) = f_2(t)$, then

$$\phi_{11}(\tau) = 1/T_1 \int_{-T_1/2}^{T_1/2} f_1(t)\, f_1(t+\tau)\, dt \qquad (6.3)$$

where ϕ_{11} is called the autocorrelation function of $f_1(t)$. The subscript 11 indicates that the autocorrelation function is obtained by correlating a function with itself.

The concept of autocorrelation plays a central role in the analysis of random functions which may contain periodic components. A situation of this sort occurs when a periodic signal is masked by random noise. The interferometer recordings in our experiments are similar signals.

6.3 CROSSCORRELATION

If, in the correlation theorem for periodic functions (equation 6.1), $f_1(t)$ and $f_2(t)$ are different periodic functions (of the same fundamental frequency), we define a crosscorrelation functions of $f_1(t)$ and $f_2(t)$ as

$$\phi_{12} = 1/T_1 \int_{-T_1/2}^{T_1/2} f_1(t)\, f_2(t + \tau)\, dt \qquad (6.4)$$

$$\phi_{21} = 1/T_1 \int_{-T_1/2}^{T_1/2} f_2(t)\, f_1(t + \tau)\, dt \qquad (6.5)$$

In equation (6.4) the subscript 12 indicates that the crosscorrelation involves $f_1(t)$ and $f_2(t)$ with the second numeral in the subscript referring to the fact that $f_2(t)$ has the displacement τ. Similar explanation holds for equation (6.5).

A notable difference between autocorrelation and crosscorrelation is that, whereas autocorrelation discards all phase information in the given function, crosscorrelation retains the phase differences of the harmonics which are present in both periodic functions. Thus, information about the relative timing between characteristic features in the wave-shapes of $f_1(t)$ and $f_2(t)$ are preserved.

6.4 SIGNAL IDENTIFICATION BY CROSSCORRELATION WITH SHARP PULSES

When any signal is received, it can best be analyzed when its useful periodic component can be separated from the noisy, random component. A detailed description of a process for recovering periodic signals buried in incoherent noise is available in the books by Y.W. Lee[3] and Mansour Javid[4]. This process consists of sampling the received signal with narrow rectangular pulses over a finite time.

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3. Refer to Statistical Theory of Communication by Y.W. Lee
4. Refer to Analysis, Transmission and Filtering of Signals, by Mansour Javid and Egon Brenner.

When the noisy signal is crosscorrelated with a periodic train of narrow pulses (impulses) having the same period as the periodic component in the noisy signal, the output obtained is proportional to the samples of the useful component in the noisy signal. This process basically amounts to taking values of the received noisy signal [say $f_1(t)$] at the instances of occurrence of the periodic unit impulses, over a sufficiently long duration, and then averaging these values for each value of the displacement. Such a process will accentuate the repetitive features in the received signal while attenuating the non-repetitive features. Also, since all the pulses are of equal area, the amplitude of the crosscorrelation reflects the pattern that is repetitive within the time interval between two successive pulses. Figure 6.1 illustrates the ideas discussed above.

Figures 6.1(a-e) illustrates this concept graphically. A sine wave generated by ILS-IEEE is shown in Figure 6.1a. Noise, whose statistics is known to us, is added to this sine wave and this is shown in 6.1b. An impulse train (Figure 6.1c) has been generated which has a frequency approximately equal to the sine wave. Figure 6.1d shows the results of crosscorrelating one record[5] of each and Figure 6.1e shows the result of crosscorrelating all thirty records over a net displacement of τ = 1.706 seconds (approximately over four periods). It is clear from Figure 6.1e that this process has recovered the sine wave and has substantially reduced the noise.

In this research work this concept of signal identification by crosscorrelation has been adopted. Pulses of uniform amplitude and width representing the R peaks of the ECG, whose frequency is the same as the repetitive features in the interferometer data, is crosscorrelated with the interferometer record. It is the R wave pulse train that is displaced by and is represented by f_2 in equation 6.4 or

5. Refer to ILS-IEEE Users Manual

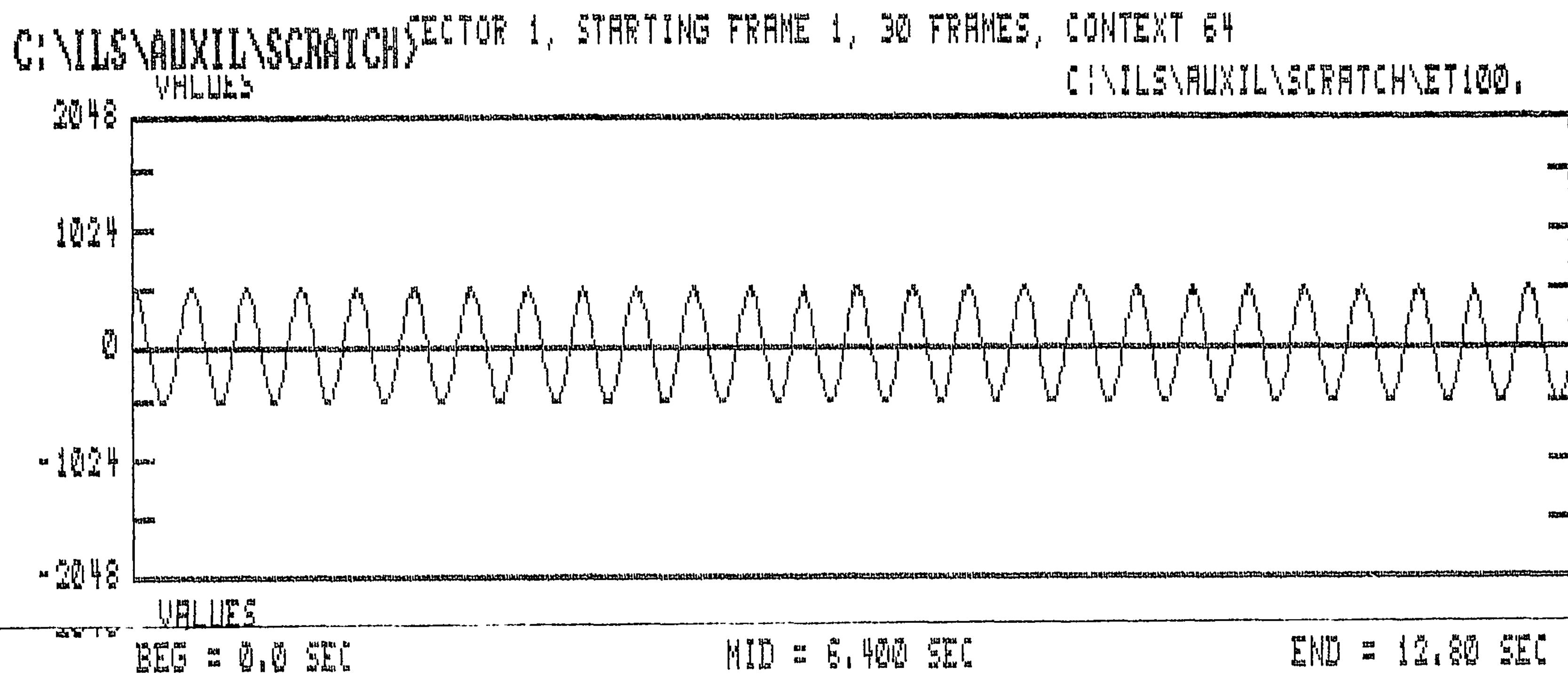

Figure 6.1 (a). A pure sine wave with a known frequency

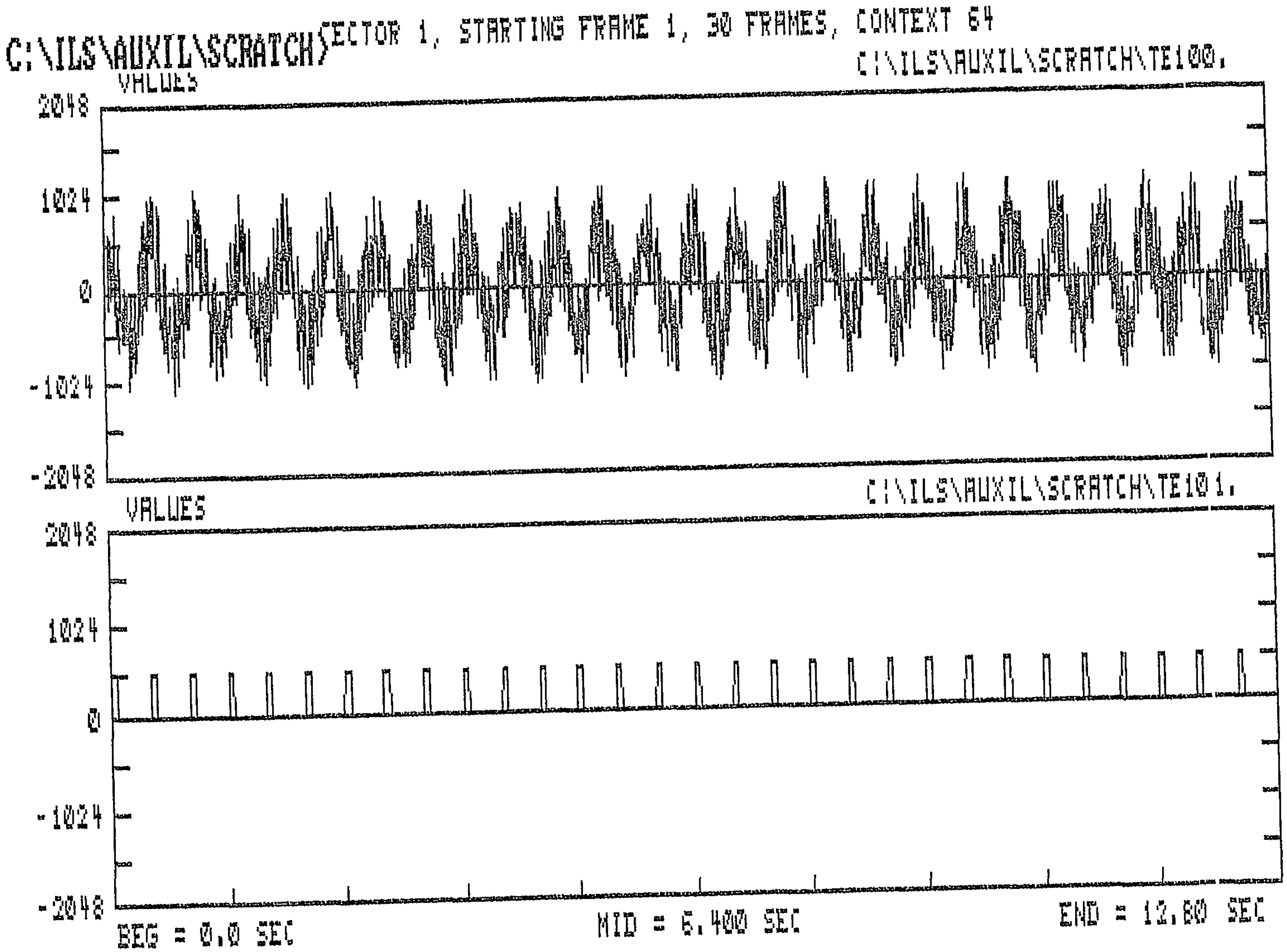

Figure 6.1(b). Noise, whose statistics is known added to the pure sine wave
(c). A pulse train whose frequency is equal to the frequency of the sine wave

C:\ILS\AUXIL\SCRATCH>pause
Strike a ley when ready . . .

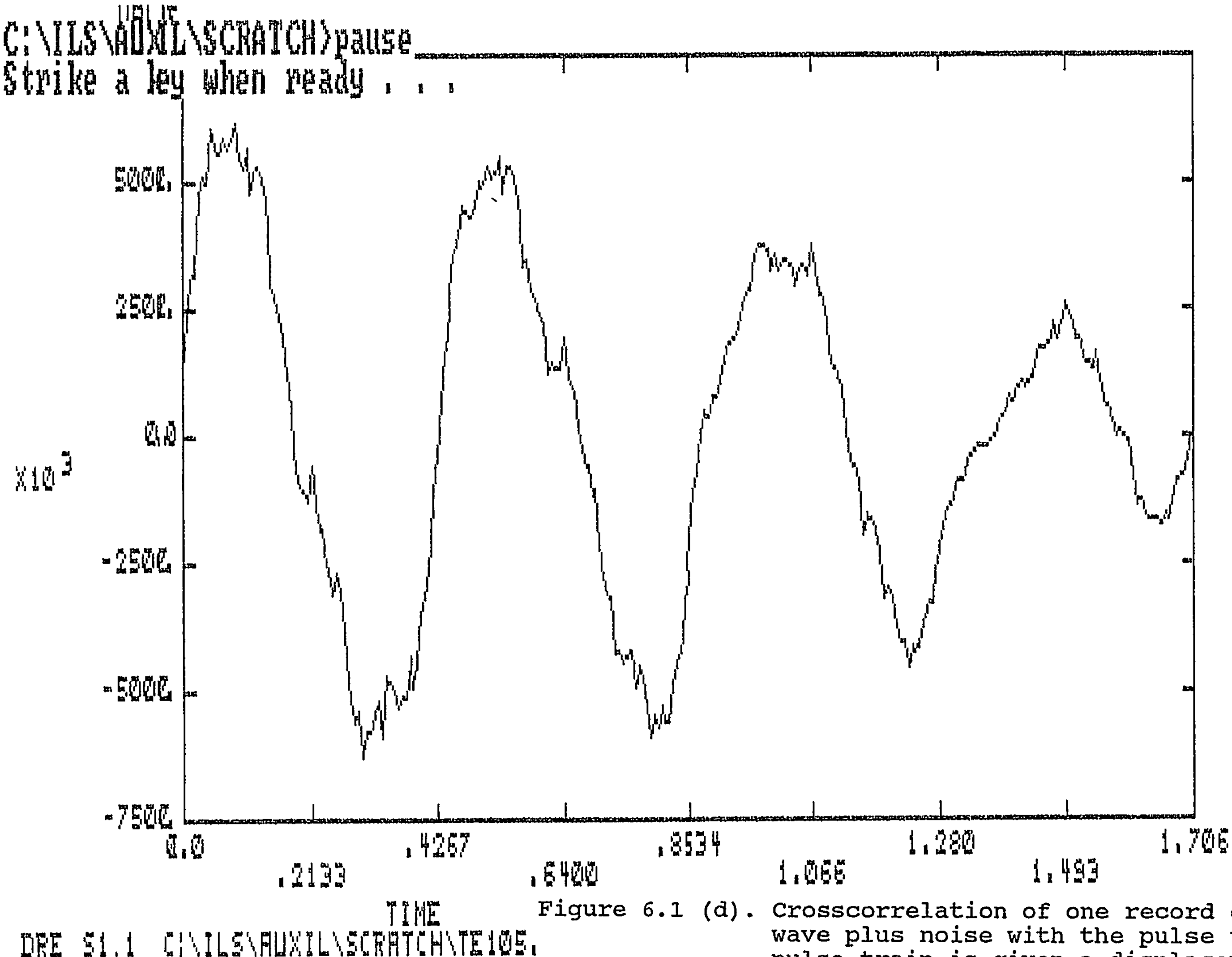

Figure 6.1 (d). Crosscorrelation of one record of the sine wave plus noise with the pulse train. The pulse train is given a displacement of τ = 1.706seconds

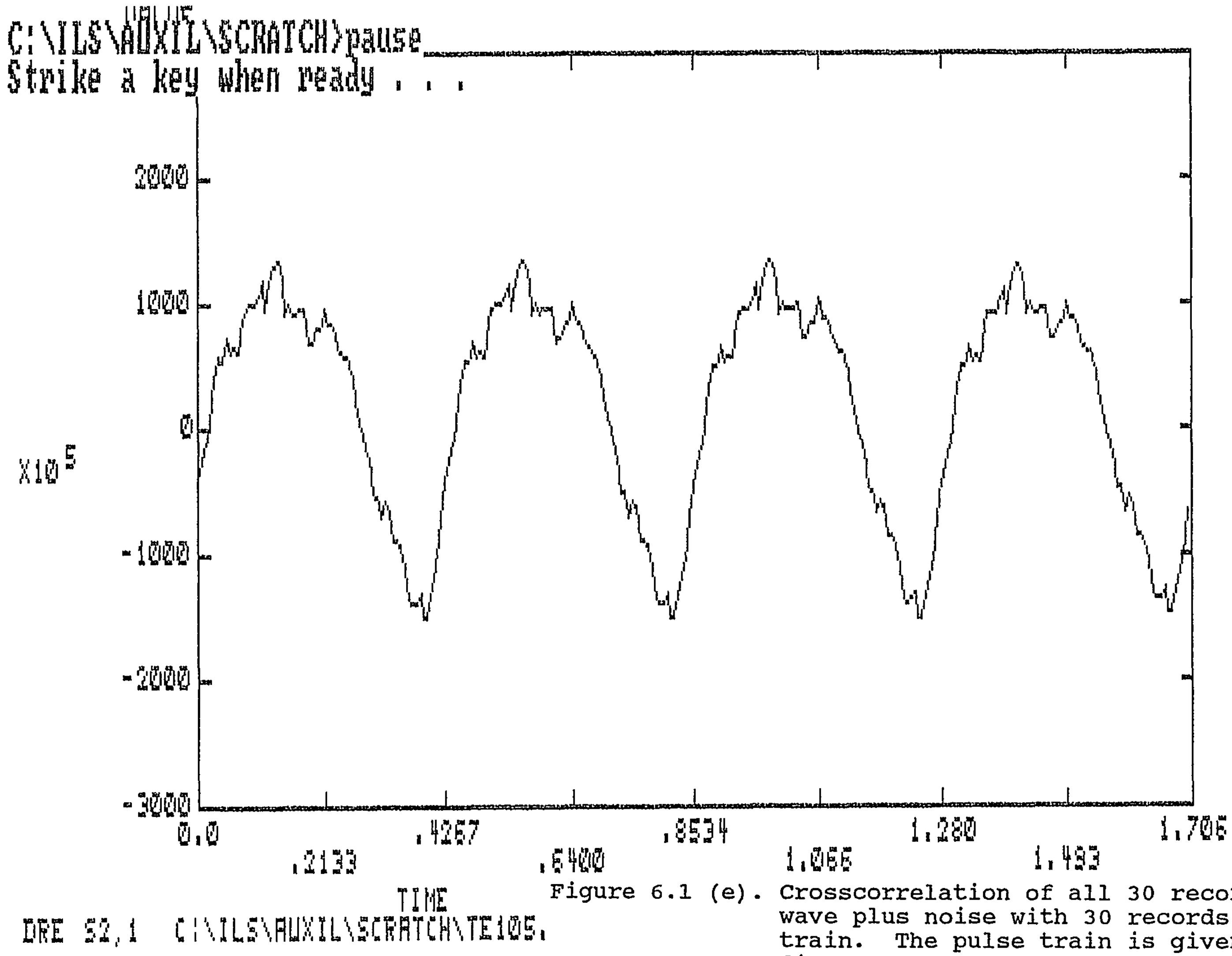

Figure 6.1 (e). Crosscorrelation of all 30 records of sine wave plus noise with 30 records of the pulse train. The pulse train is given a net displacement of τ = 1.706 seconds.

f_1 in equation 6.5. The result of the crosscorrelation will be a smoothened version of the interferometer record as a function of the displacement τ; an R wave occurs at $\tau = 0$; thus the timing of the features in the interferometer record can be measured relative to the R wave.

CHAPTER VII
SIGNAL PROCESSING
USING ILS IEEE SOFTWARE PACKAGE

7.1 INTRODUCTION TO ILS-IEEE

Following the procedures described in the Chapter on Experimental Setup we obtain the three signals XX99, XX100, XX101, which are the raw digitized ECG, the digitized interferometer signal and the pulse train representing the R waves of the ECG respectively. A brief introduction to the ILS IEEE signal processing software is given below. A step by step description on using the command language of ILS IEEE for the purpose of this research work will follow. For a more detailed description the reader is referred to the ILS users manual.

The ILS IEEE package is a user-level software system for interactive signal processing. It is a subset of the commercially available full ILS (Interactive Laboratory System). ILS IEEE has a modular set of functions which teams with a suitably configured IBM personal computer to work as an integrated software system. Using the command language of ILS one can perform a variety of signal processing and analysis and the following are few selected examples.

1. Signal Display : Signals may be displayed as numeric values or as waveforms.
2. Signal Editing : Using the cursor capability of ILS, waveforms can be edited.
3. Data Processing : These capabilities include modifying data values, performing certain arithmetic using the data, multiplexing and demultiplexing and moving data within and between the files.
4. Signal processing : Among other available functions, ILS can perform autocorrelation and crosscorrelation by means of the Fourier Transform (FFT).

5. Spectral Analysis : It can display two dimensional and three dimensional spectra of signals.

6. Digital Filtering : Linear phase filters such as Chevychev, Butterworth, and Elliptic filters can be designed and implemented using ILS.

7.1.1 File Structure of ILS IEEE

The two main types of files in ILS are:

i) Sample-data files

ii) Record files

Digitized signals are stored in sample-data files. Sampled data take the form of 16-bit binary values (-32768 to +32767). Unlike sample-data files, in which data are stored as fixed point integers, record files use floating-point representation. Record files may contain complex numbers and some ILS commands actually permit operations on complex quantities. The ILS command SRE[6] is used to convert sample-data files to record data files and the command SSD performs the reverse operation.

7.2 USING ILS-IEEE

A step by step documentation of the way ILS has been used in this research is as follows. At the very beginning the AUTOEXEC.BAT[7] file has to be executed in order to set up the proper environment and also to boot ILS to the system. The command ILS C is executed next by keying in ILS C to the C:\ prompt. This creates and initializes the ILS COMMAND file CM9999. CM9999 must reside in the current working disk directory. Its function is to communicate parameter

6. See Appendix (A-6)
7. See Appendix (A-1)

values from one program to another. The ILS C command needs to be run only once at the beginning of a work session.

Following this the command FIL ANXX is executed which selects all files with prefixes XX in the default directory for ILS files.

The INA command in ILS is used to initialize a non-ILS file with an ILS file header and to enter numerical analysis parameters required by various ILS commands which use sampled-data files. These parameters are, for example, file size, sampling frequency and file identification. The header is one disk block long; the first 64 words are used by ILS, and the remaining words are available for optional user-supplied information. The following header values need to be checked and changed if necessary: sampling frequency, sampled data frames, and Hamming window. In our case for example, the INA command is used to set up the following values which is accomplished by keying in the following sequence of commands:

FIL 100 ;this selects file XX100 for initialization.

INA SF150 ;this sets the sampling frequency in the file header to 150 samples/second (or Hz.)

INA SD30 ;this sets the number of sampled data frames to 30 at the default context[8] of 64 points/frame.

INA HMY ;this sets Hamming window process in file header

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8. Refer to Users manual of ILS-IEEE

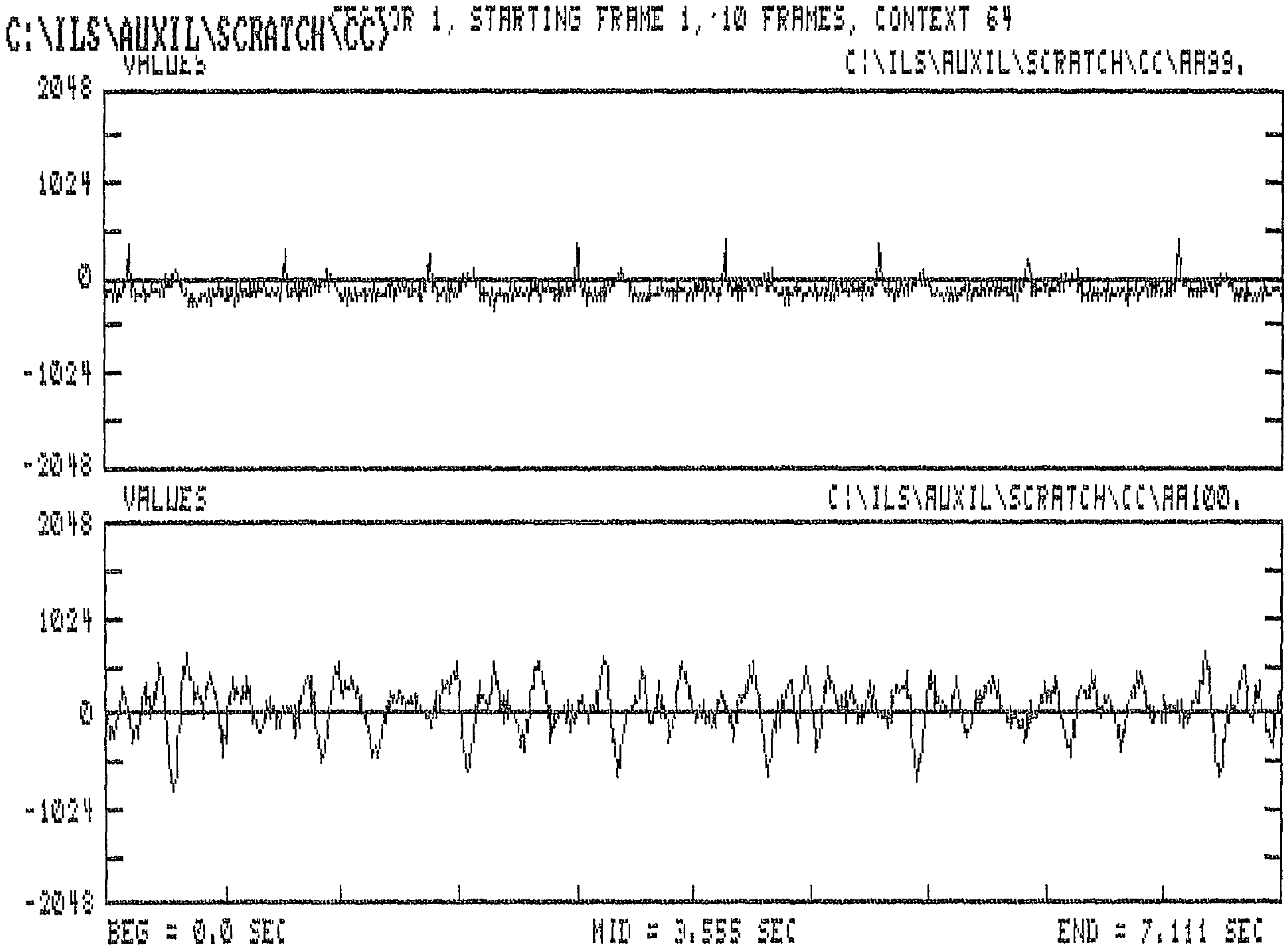

Figure 7.1 The execution of the ILS-IEEE command
DSP E1,10,,,,2
displays ten frames from two consecutive files
starting at frame 1 and ending at frame 10

The data can now be presented graphically in the time domain. Having selected file xx99 with the command FIL 99, we key in : DSP E1,10,,,,2

This will display ten frames of data, starting from frame 1 up to frame 10, for two successive files (file XX99 and XX100 containing the digitized ECG and interferometer record, as mentioned before). This result is shown in Figure (7.1) whose top trace is the digitized ECG record and the bottom trace is the digitized interferometer record.

As stated in the chapter on theory of correlation, an autocorrelation process will accentuate those features in a signal that are repetitive and attenuate those that are non-repetitive. Based on this idea, research work has been done by Eric Ho[9] and very interesting and encouraging results were obtained. The interferometer data, in XX100, can be autocorrelated by executing a sequence of ILS commands. This sequence of commands has been stored in order in a batch file called AUTOMI.BAT[10]. Having executed the

FIL ANXX command,

autocorrelation of the interferometer signal can be very simply performed by keying AUTOMI at the default directory. For a detailed understanding of the autocorrelation program the reader is referred to Appendix (A6.2). A typical result obtained by autocorrelation is shown in Figure 7.2.

The result of autocorrelation plotted graphically shows:

certain major velocity peaks indicating certain mechanical cardiac events that are repetitive in each cardiac cycle. The relative time between two peaks can be measured, but the instant in the cardiac cycle at which any peak occurs relative to a known event, such as the R wave, can not be identified. The R-R interval in

9. See Masters Thesis by Ho, Chin Yee Eric, NJIT, 1988
10. See Appendix (A-6)

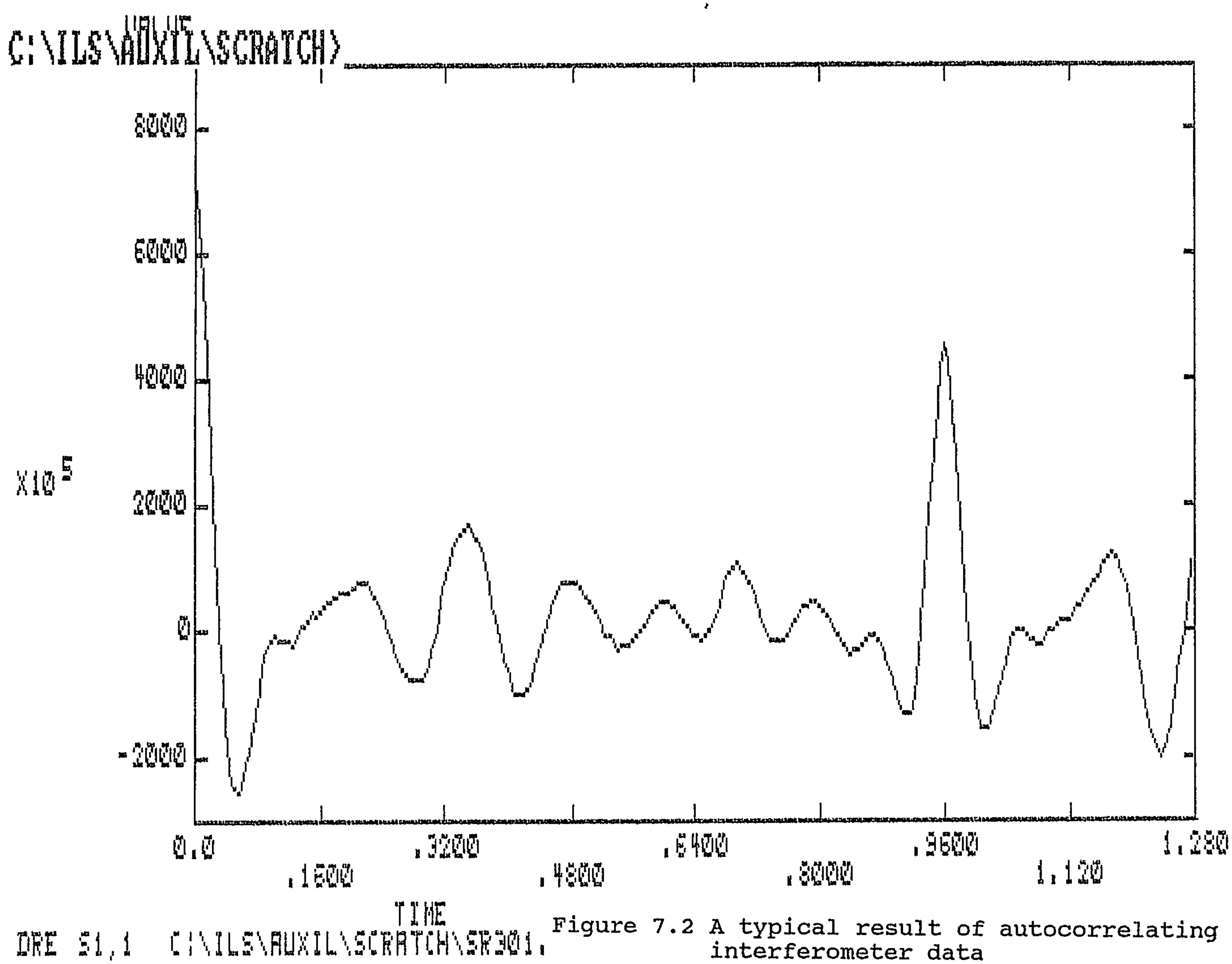

Figure 7.2 A typical result of autocorrelating digitized interferometer data

Fig. 7.2 is represented by the time between $\tau = 0$ and the peak at $\tau = 0.96$ seconds; the peak at 0.96 seconds coincides with a major peak recorded when the ECG record is autocorrelated.(The ECG autocorrelation is not shown here.) In order to relate the timing of the measured peaks to the timing of the events of the cardiac cycle, such as the R-peak of the ECG, it was necessary that the interferometer records of a subject be crosscorrelated with a pulse train representing the R-peaks of the same subject. This approach holds high potential of identifying the timing of a measured mechanical event relative to the timing of a known electrical event.

To cross correlate the data from the interferometer with the ECG R-peak pulse train a set of ILS commands must be run in a certain sequence. To avoid repetitive keying of commands, a batch file called CROSSCOR.BAT[11] was created which stores all the commands in the right sequence. To perform the crosscorrelation, the two files XX100 and XX101 must be in the default directory and they must be initialized by the command FIL ANXX. To execute the crosscorrelation one has only to key in the word CROSSCOR in response to the C:\ prompt. As the program runs certain plots are seen on screen while the user is given instructions on how to continue ahead. The plots can be printed out one at a time by keying in Shift and PrtSc simultaneously and a set of typical results are shown in Figures 7.3(a-e). Fig 7.3 a and b are the digitized interferometer and the pulse train representing the R waves of the ECG. Figure 7.3c shows one record of each of the above data which when crosscorrelated gives Fig 7.3d as result. Data are collected from each subject for about 60 seconds. If all 60 seconds of data are crosscorrelated we get the result as shown in Fig 7.3e where the noise is substantially reduced.

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11. See Appendix (A-6)

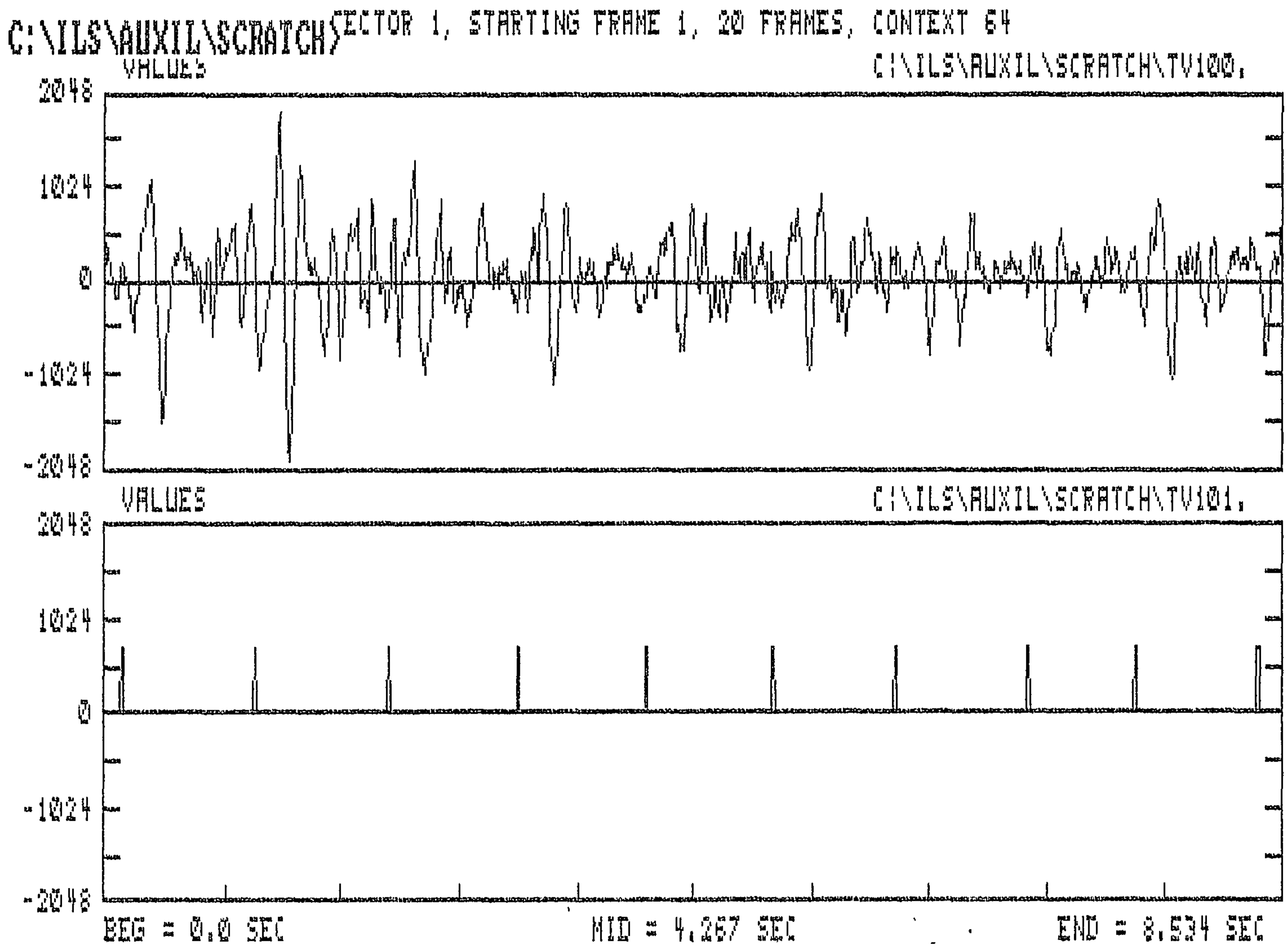


Figure 7.3(a). Twenty frames of digitized interferometer data
(b) Twenty frames of the pulse train obtained from the ECG. The pulse represent the R waves

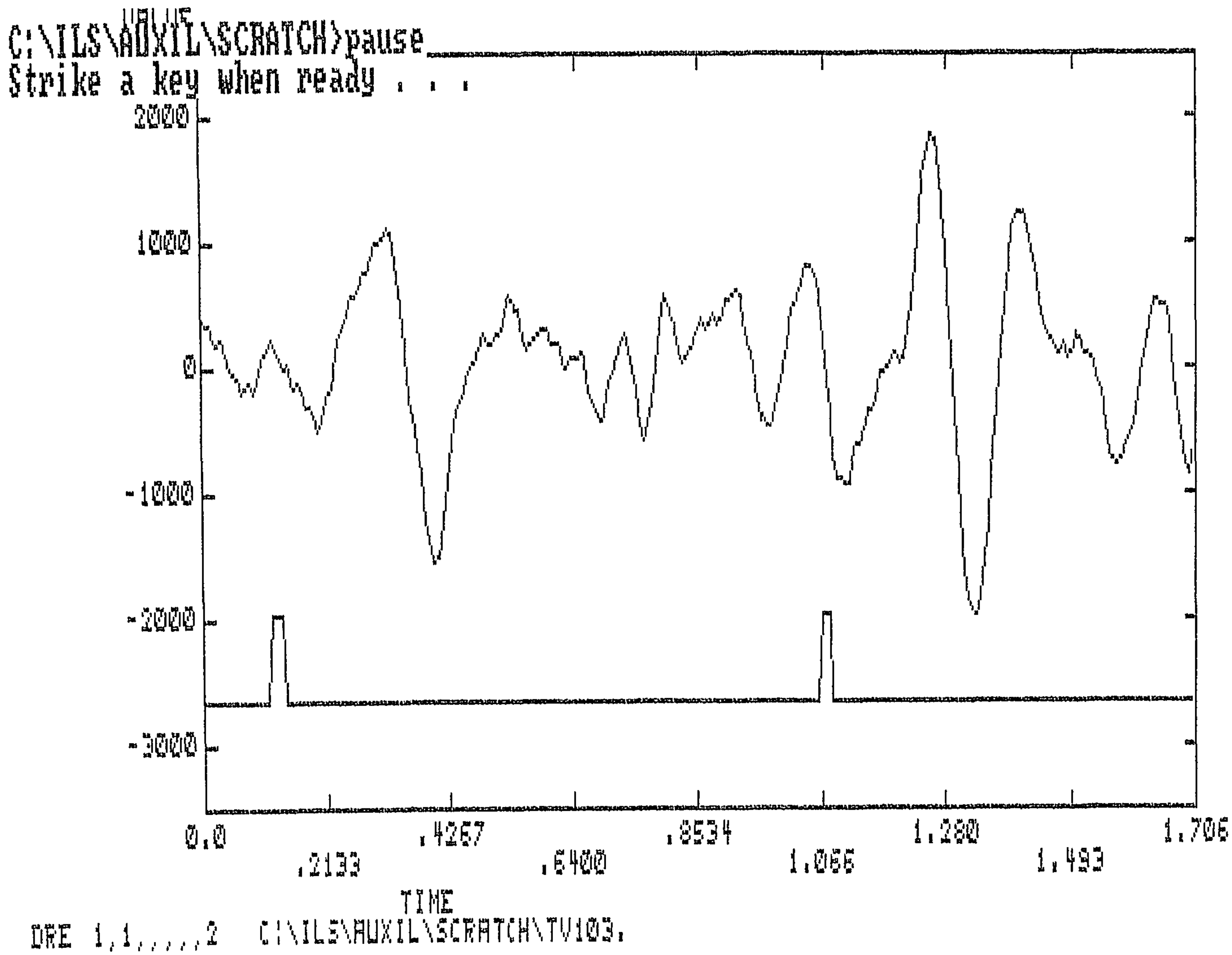


Figure 7.3(c). One record each from digitized interferometer data and from the digitized ECG

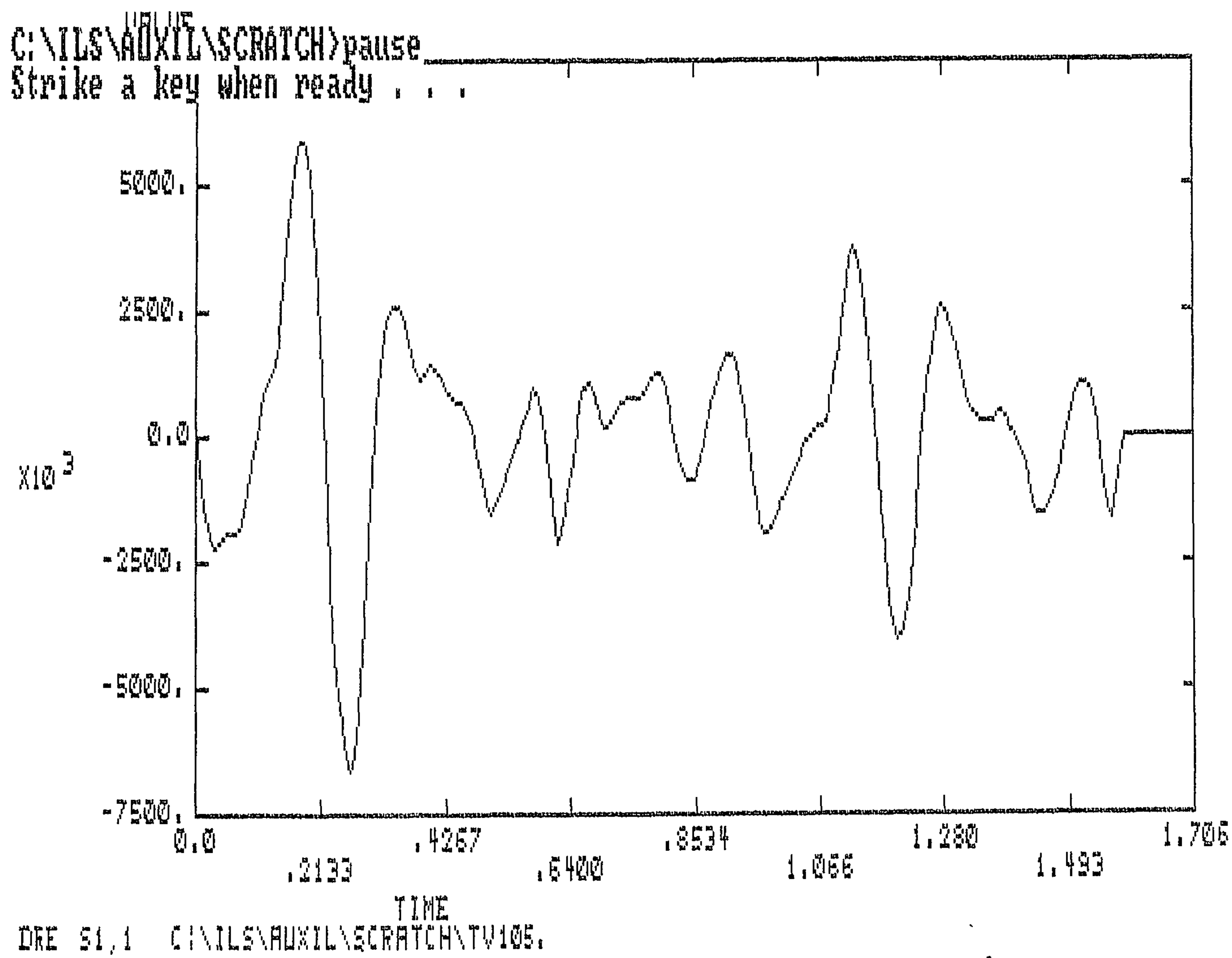


Figure 7.3(d). Result of crosscorrelating one record of interferometer data with one record of the ECG pulse train. The ECG pulse train is given a net displacement of τ = 1.706

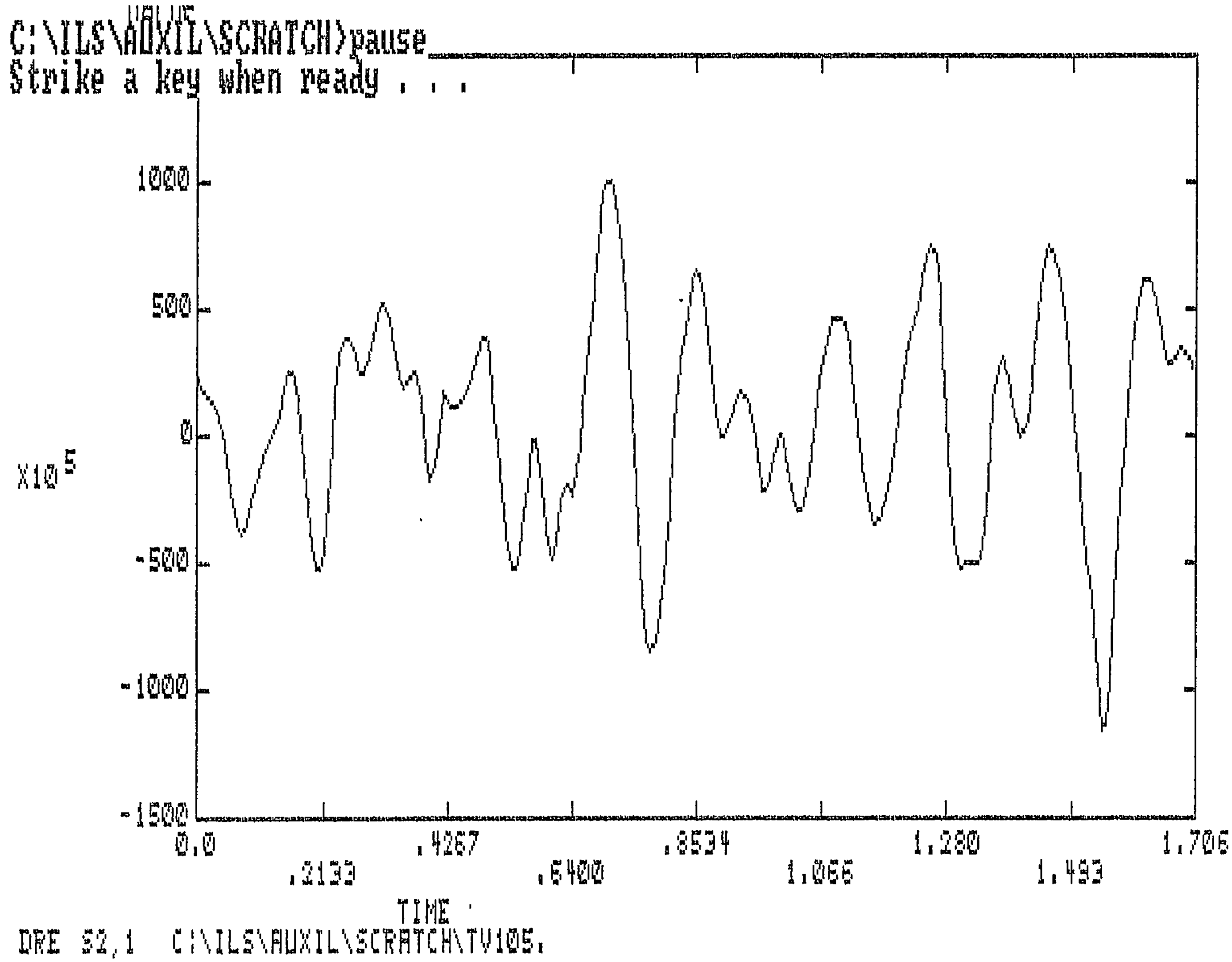


Figure 7.3(e). Result of crosscorrelating all thirty records of interferometer data with thirty records of the ECG pulse train. The ECG pulse train is given a net displacement of τ = 1.706

CHAPTER VIII
EXPERIMENTAL RESULTS AND CONCLUSIONS

8.1 EXPERIMENTAL PROCEDURE

The overall experimental set-up has been described in Chapter (III). Interferometer and ECG data were collected simultaneously from 18 consenting[12] students at New Jersey Institute of Technology, ten males and eight females. All of them were of normal health and with no known heart diseases. The data also included other information such as sex, age, height, weight and pulse rate at the time of experimentation.

All the subjects were made to lie down on a laboratory bench, first in a supine position and then on their stomachs, with the microwave interferometer illuminating their anterior (or posterior, depending on the position) chest wall. ECG electrodes were also attached to the subjects. With the subjects lying down and breathing normally two channel data were displayed on an oscilloscope until regular, good quality rhythmic signals synchronized with the heart rate were observed; these data were finally acquired[13]. The data collected are then processed on an IBM-AT personal computer as has been already described in the sections on data processing.

12. See consent form in Appendix (C)
13. See Data Acquisition procedure in Chapter (IV)

8.2 ANALYSIS OF PROCESSED DATA

The interferometer and ECG recordings of two representative male and two representative female students, lying in a supine position are shown in Figure 8.1(a-d). The recordings are from the anterior (front) chest wall. Negative deflection of the interferometer axis represent velocity vectors towards the interferometer antenna, i.e. upward motion of the chest wall. There appears to be a pattern in the high-velocity chest wall vibrations recorded by the interferometer which are distorted by noise and artifacts[14]. This fact is verified by the eighteen sets of signals collected. In all eighteen samples a distinct peak occurs with a fixed delay soon after the R wave of the ECG.

The amplitude of the interferometer record is modulated by what appears to be the respiratory cycle. It is hypothesized that respiration affects the elasticity of the chest wall and hence the velocity with which the chest wall vibrates.

Recordings from the interferometer have been autocorrelated in the past[15]. The process of correlation was meant to emphasize the repeating pattern at the expense of the noise and artifacts. Figure 8.2 illustrates the result of autocorrelation[16]. Figures 8.2(a) and 8.2(b) are the results of autocorrelating the interferometer and the ECG signals respectively. Approximately 30 seconds of data, or 30 heart beats, are subjected to the autocorrelation operation. The autocorrelation function will accentuate those functions that are cyclically repetitive within the record and attenuate the non-repetitive features. The high amplitude peak (maxima) around

---

14. Refer to 'A Microwave Interferometer as a Non-contacting Cardiopulmonary Monitor',P.E.Engler et al, Proc. N.E. Bioengineering Conf.,Durham, N.H, 1988.
15. Refer to Masters Thesis by Ho, Chin Yee Eric, NJIT, 1988.
16. See Appendix (A-6) for listing of AUTOCORR.BAT program

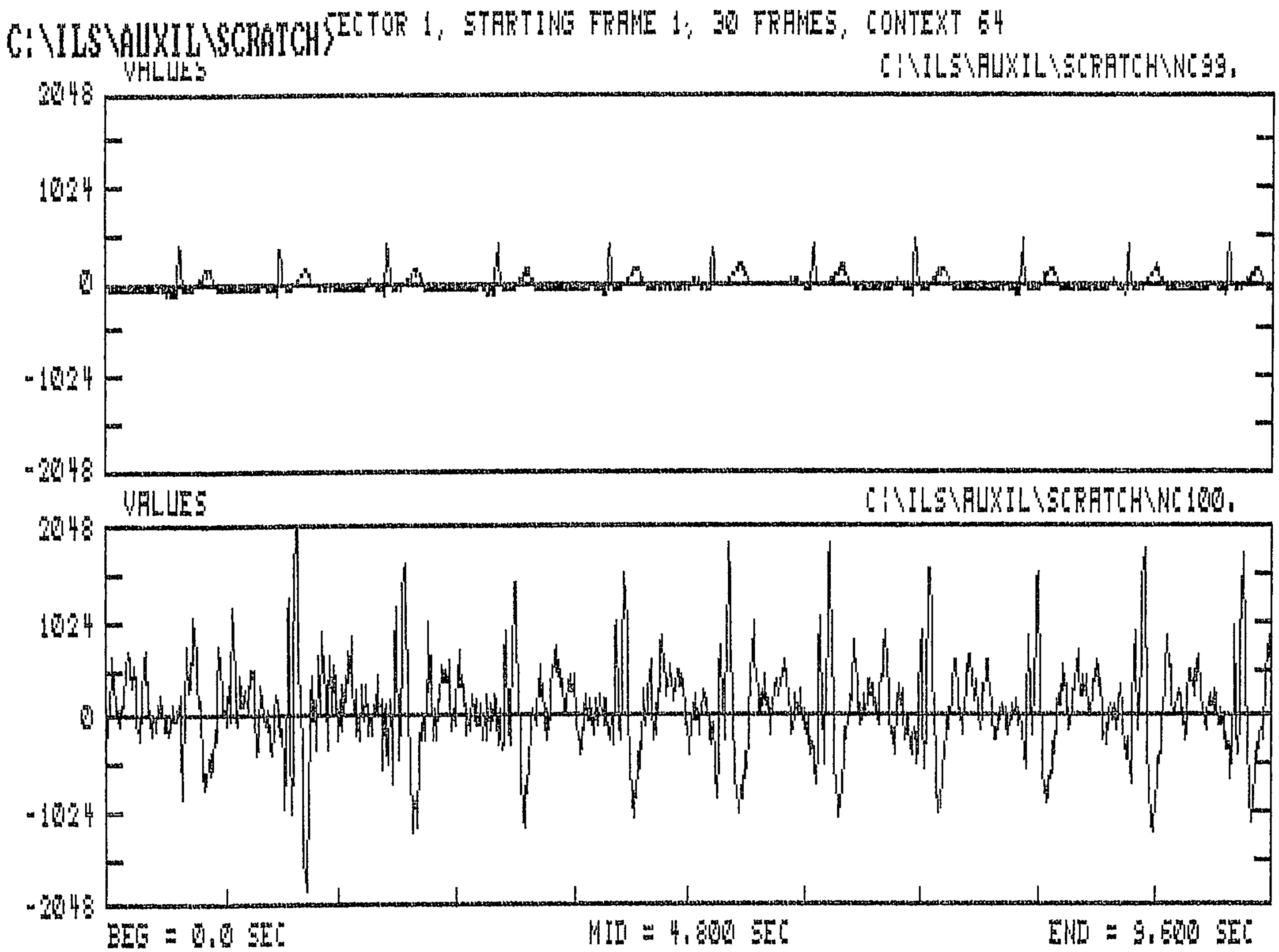


Figure 8.1(a). Thirty frames of digitized ECG (a) and Interferometer (b) recordins from representative male #1.

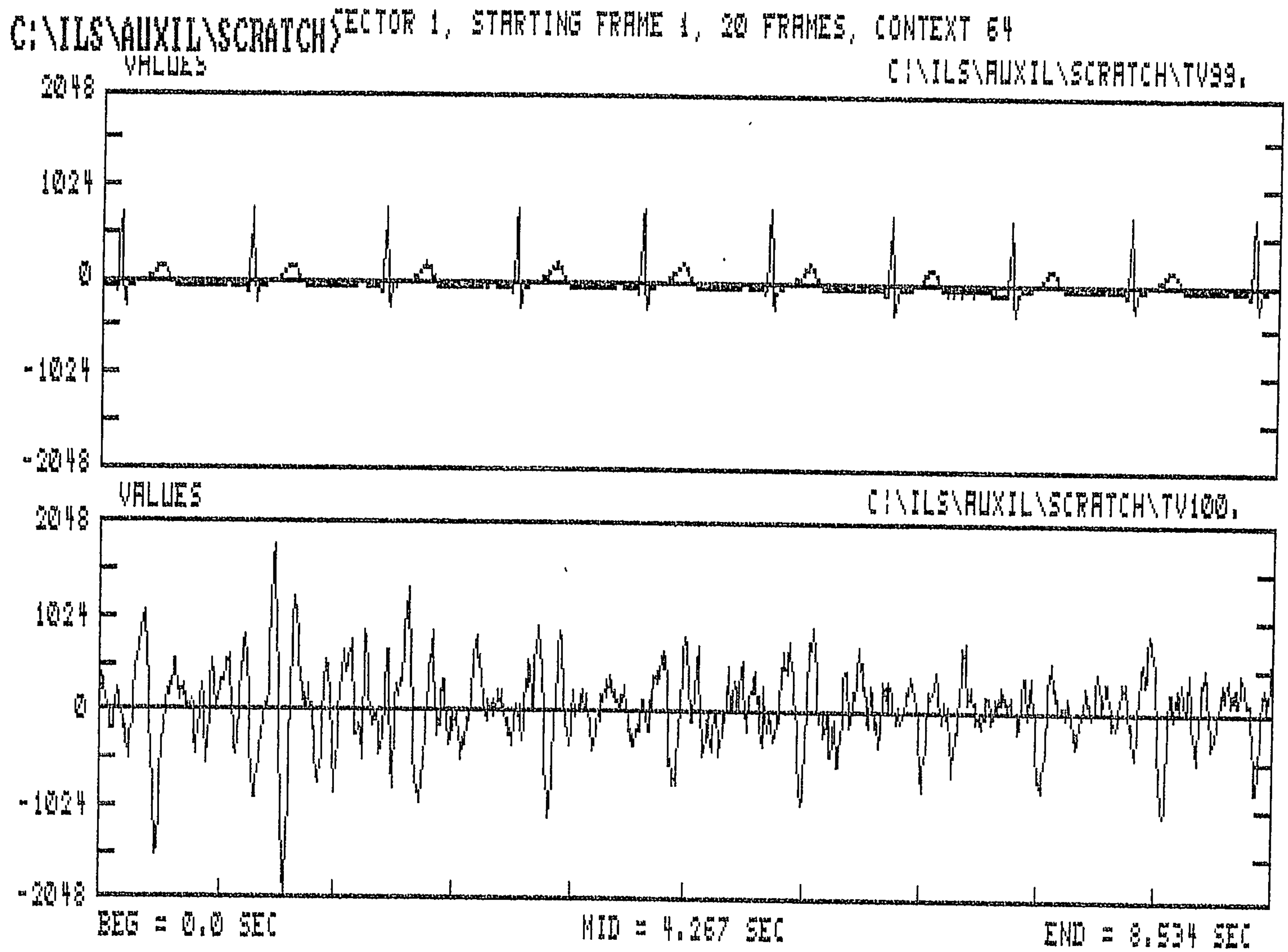


Figure 8.1(b) Thirty frames of digitized ECG (a) and Interferometer (b) recordins from representative male #2.

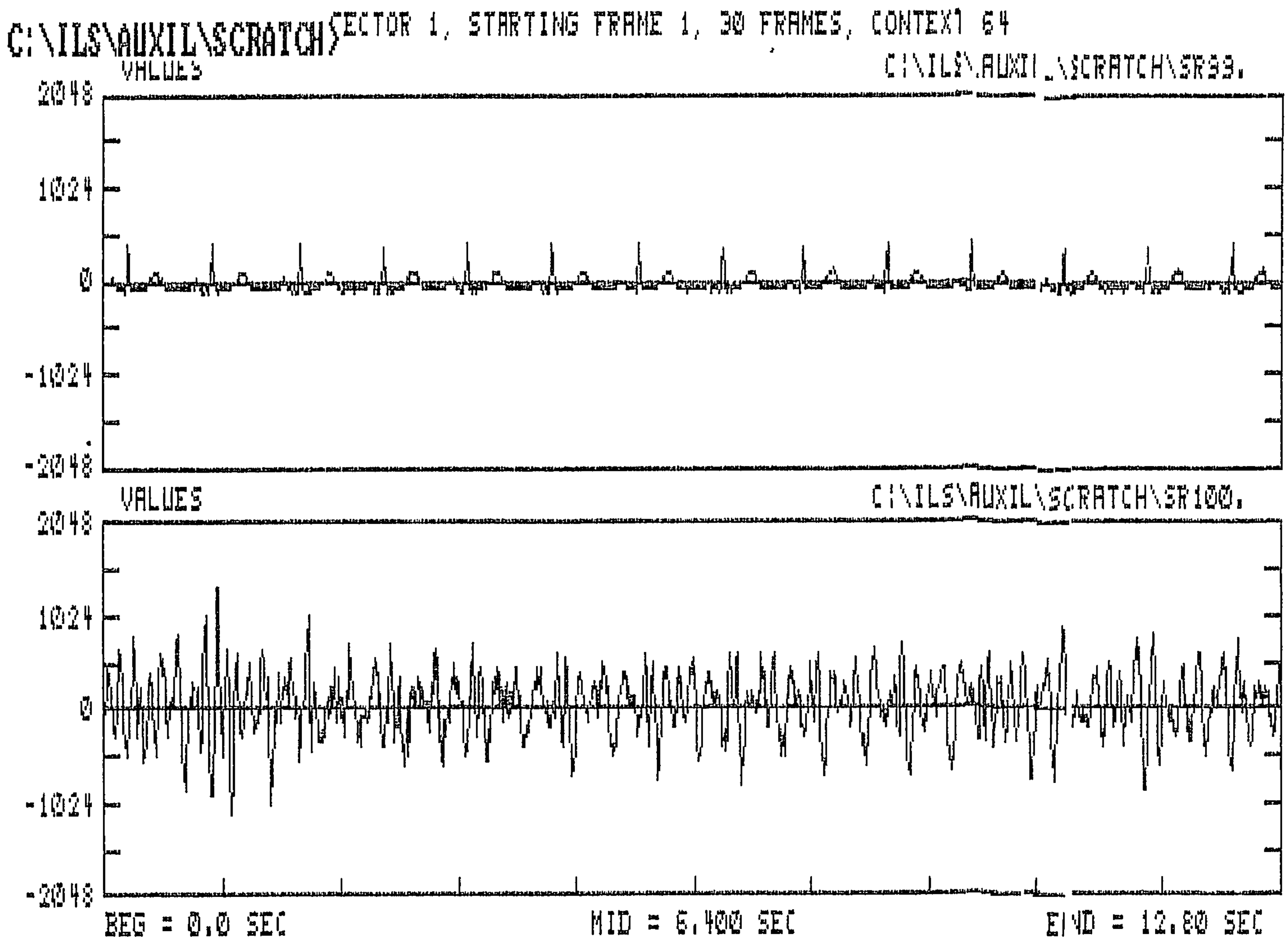


Figure 8.1(c) Thirty frames of digitized ECG (a) and Interferometer (b) recordins from representative female subject #1.

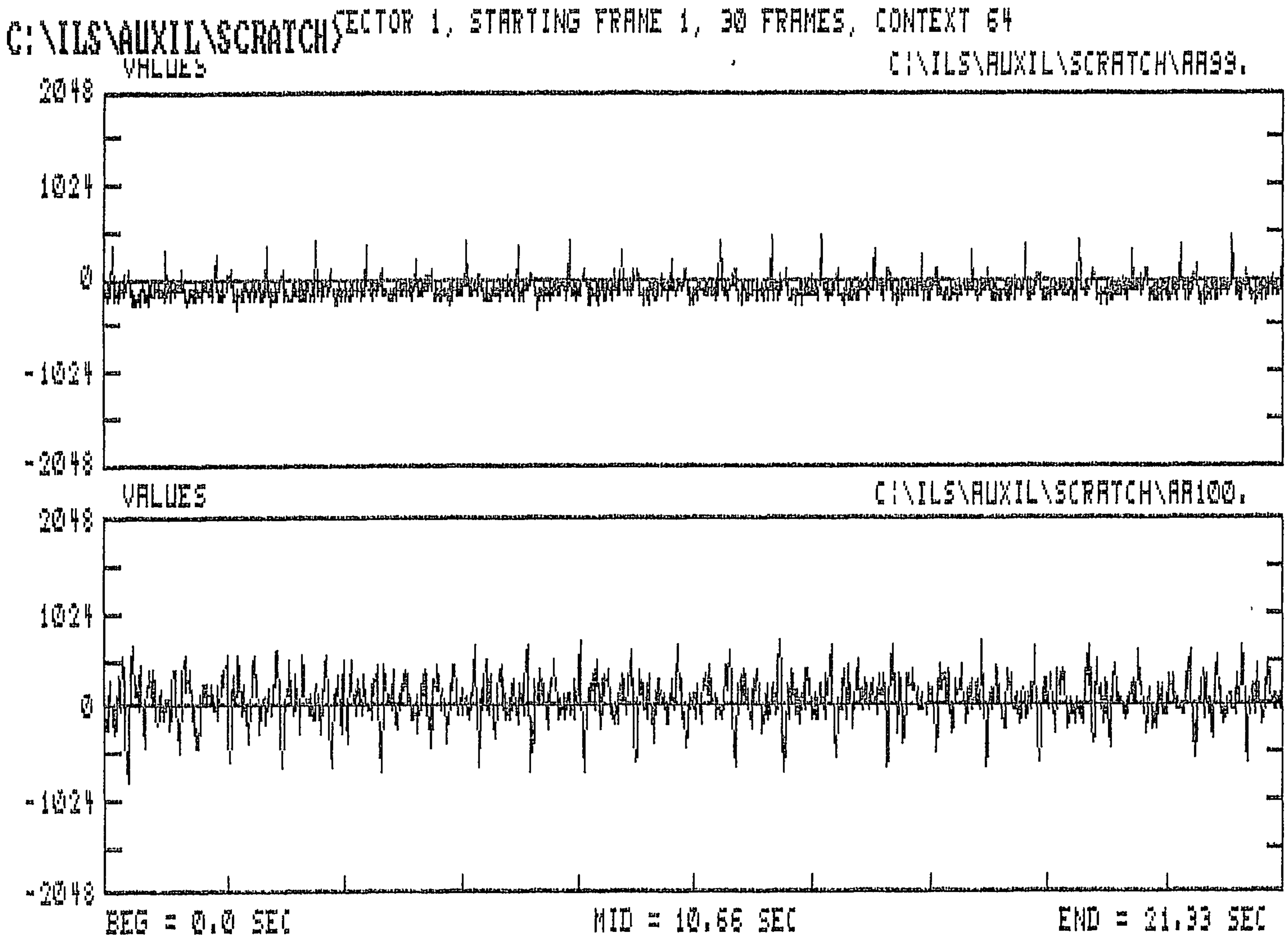


Figure 8.1(d) Thirty frames of digitized ECG (a) and Interferometer (b) recordins from representative female subject #2.

τ= 0.768 second delay mark in figure 8.2(a) represents the interpulse interval. This fact may be verified by the autocorrelated result of the ECG records of the same subject which exhibits a major peak at the identical autocorrelation delay parameter [See Figure 8.2(b)]. Similar results have been observed on autocorrelating the entire data library. Also, within each cardiac cycle, there are almost always four peaks representing high velocity deflections of the chest wall that occur at most of the 30 or so cardiac cycles of these records. These peaks or deflections are fairly wide, and relatively indistinct because the heart rate or the R - R interval is not quite constant over the time during which data is collected.

The abscissa in Figure 8.2(a) measures the delay parameter, in seconds, of the autocorrelation function; the relative time between two peaks can be measured, but the instant in the cardiac cycle at which any peak occurs relative to a known event, such as the R wave, is not identified. In order to relate the timing of the measured peaks to the timing of known events in the cardiac cycle, such as the R wave of the ECG, it was necessary to crosscorrelate the interferometer records of a subject with the R wave of the ECG record taken simultaneously.

A typical digitized interferometer (top) and 'R' wave pulse-train (bottom) data of one other representative subject is shown in Figure 8.3(a,b). The subject is a 27 years old male, weighing 162lbs with height 68 inches. As described in the earlier section on data processing, Figure 8.3(b) is obtained from the ECG of the subject where all R peaks are replaced by rectangular pulses of equal width and all other features of the ECG are eliminated. Figure 8.3(c) is the crosscorrelation of the interferometer data [Figure 8.3(a)] with the rectangular R wave pulse train [Figure 8.3(b)]; approximately two cardiac cycles of crosscorrelated data are depicted in Figure 8.3(c). The delay parameter τ ranges from 0 to 1.706 seconds

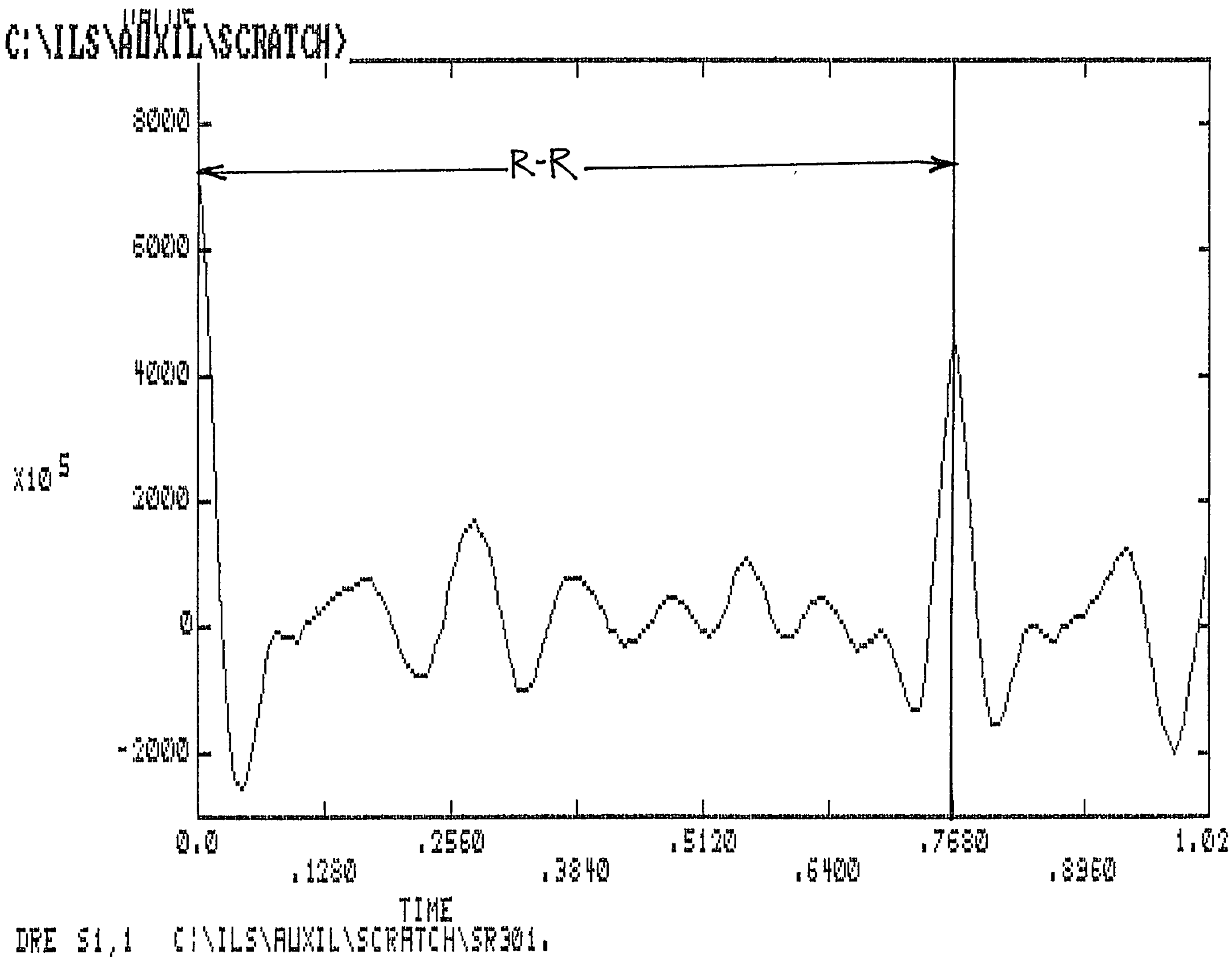


Figure 8.2(a) Result of autocorrelating interferometer data
The RR interval is as shown.

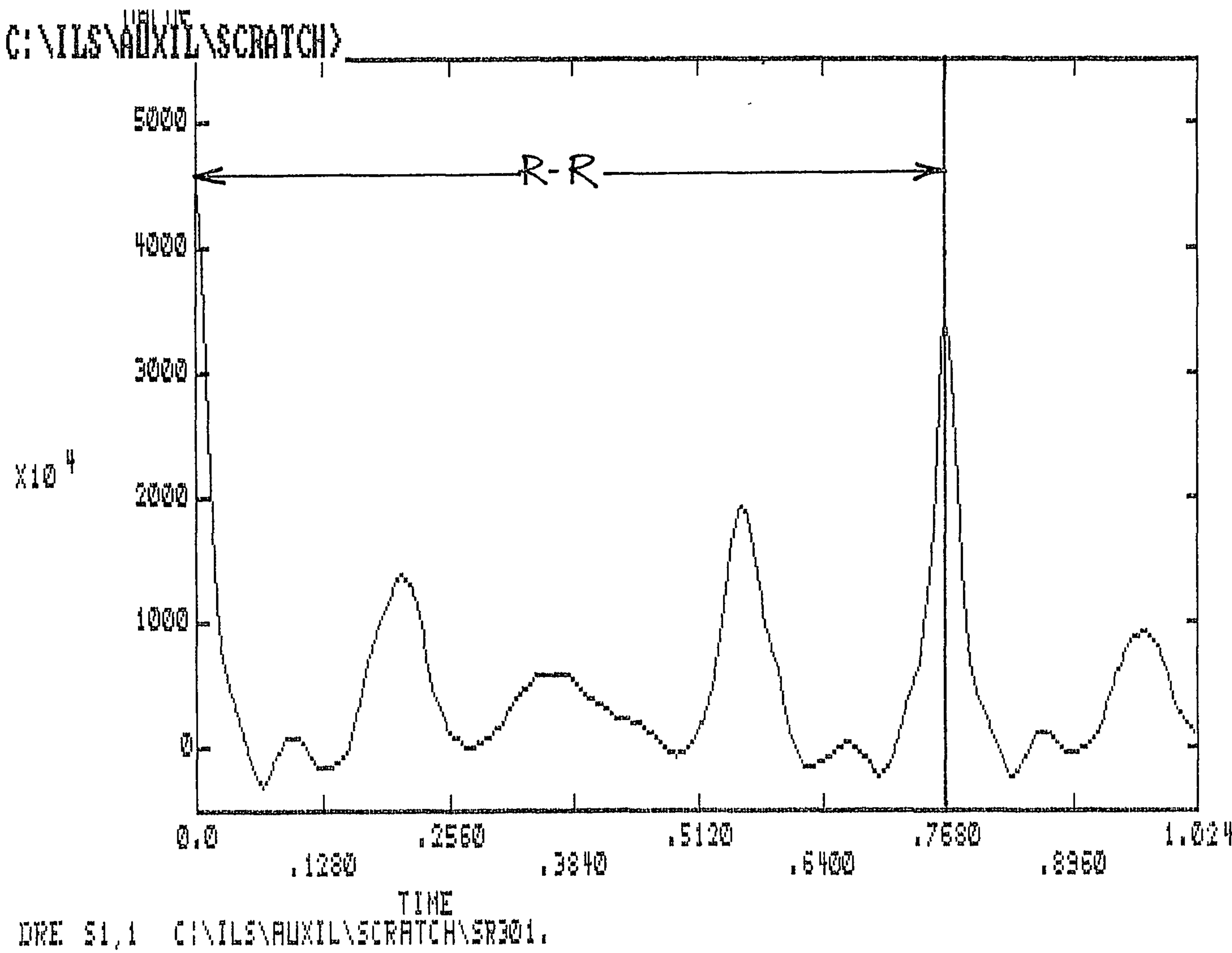


Figure 8.2(b) Result of autocorrelating ECG data
The RR interval is as shown.

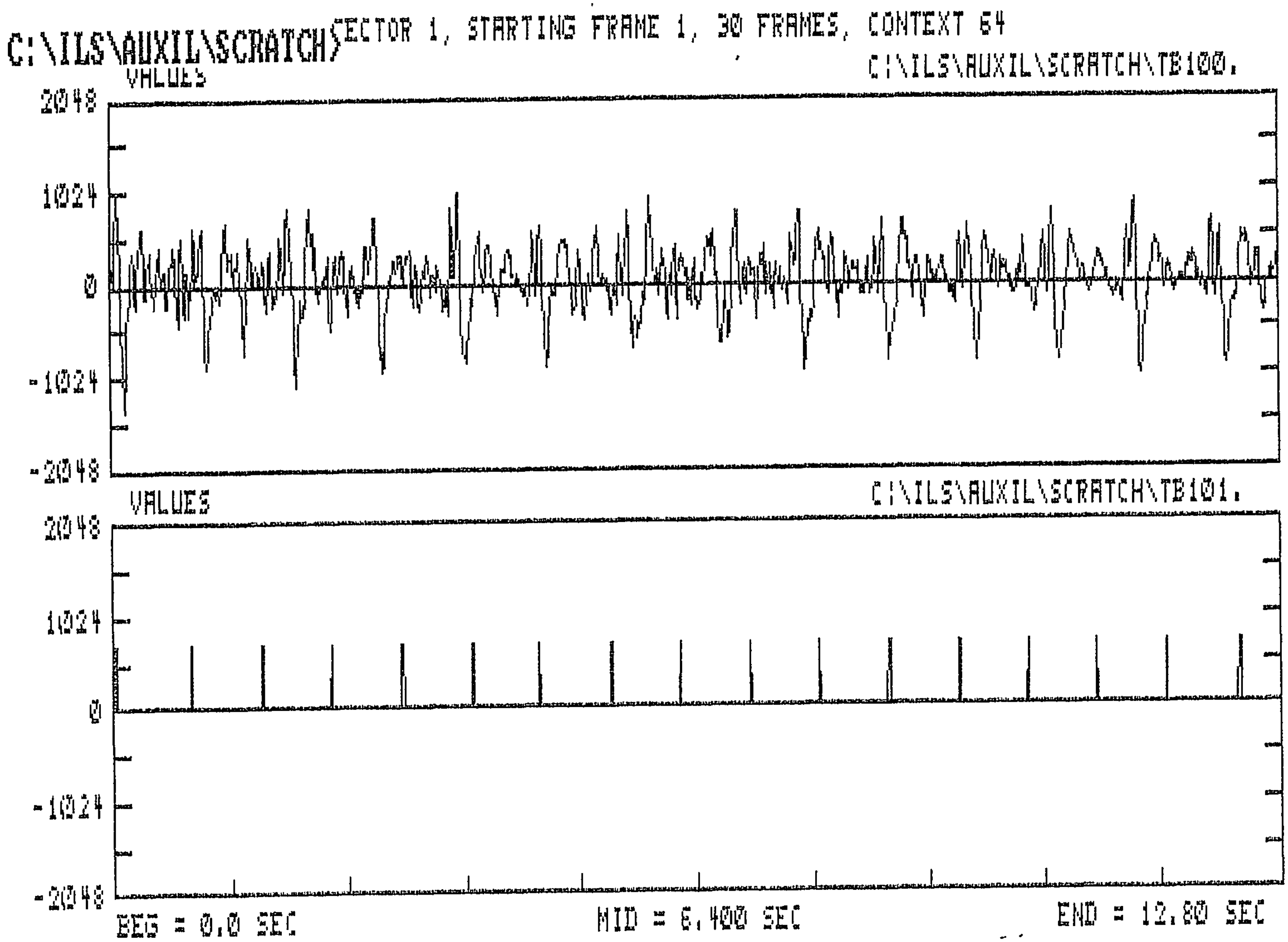


Figure 8.3(a). Digitized interferometer data from a male subject who is 27 years old, weighs 162 lbs, and is 68 inches tall.

Figure 8.3(b). Digitized pulse train where the pulses represent the R peaks in the ECG of the same 27 years old male subject, weighing 162 lbs and 68 inches tall.

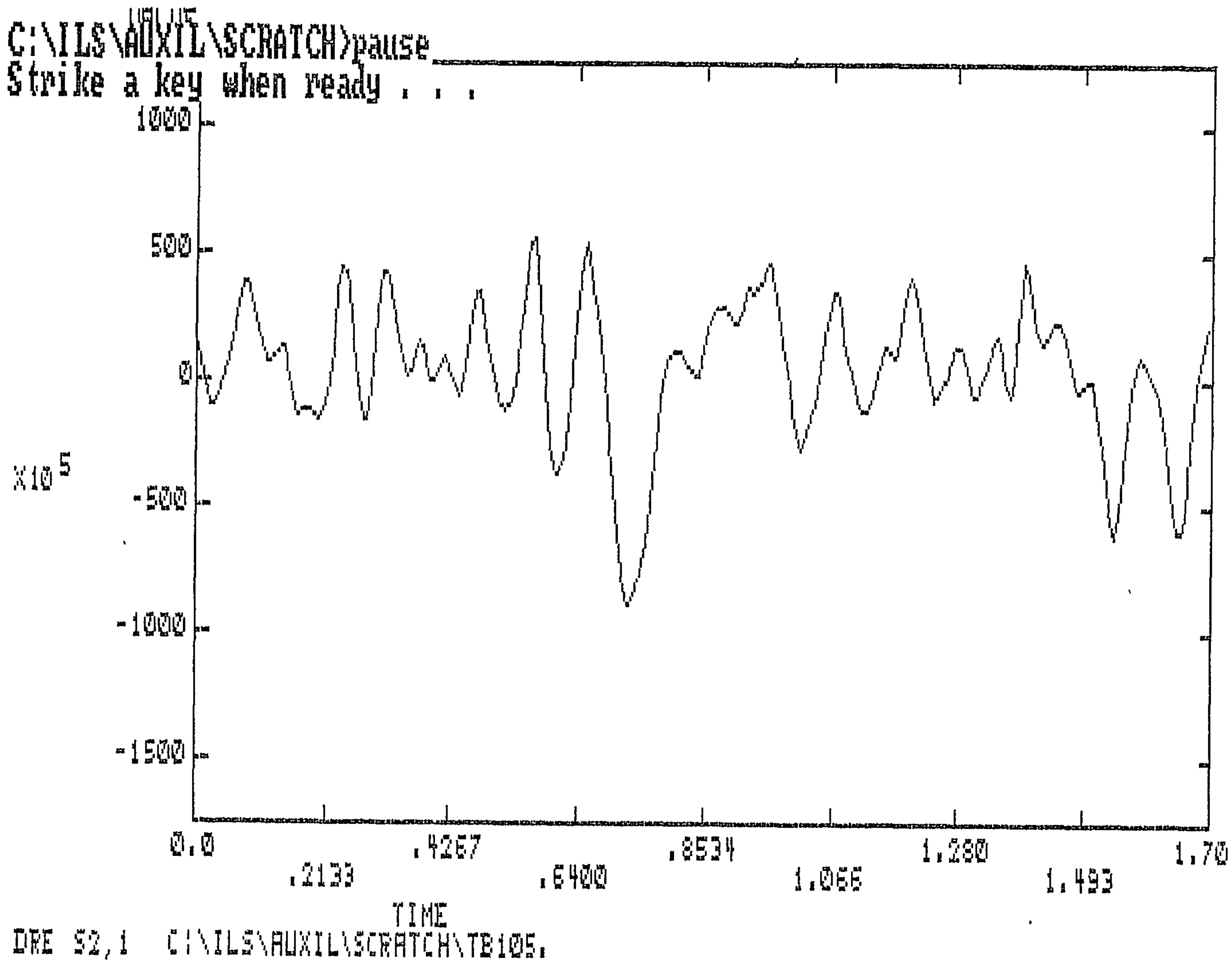


Figure 8.3(c). Result of crosscorrelating the signal of Figure 3.8(a) with the signal of Figure 3.8(b). The pulse train in #.8(b) is given a net displacement of τ = 1.706 seconds. An R-R interval is as marked.

which corresponds to roughly two cardiac cycles. Because each rectangular pulse that represents the R wave is of equal area, the amplitude of the crosscorrelation reflects the velocity of the vibration pattern that is repetitive in the two cardiac cycles covered by the delay parameter τ. An R wave occurs at $\tau = 0$.

An attempt has been made to relate the peaks in Figure 8.3(d) to the mechanical events of the heart. In order to do so, some arithmetic was done to mark the occurrence of the various peaks in terms of fractions of an R - R interval. Since the R - R interval is not constant and does vary over time, the average R - R interval in the ECG of a subject is measured from a section of the long train of ECG. Such a calculation with reference to Figure 8.4(c) is shown in Worksheet 1. This average value is marked out as an R - R interval in the crosscorrelated output [See Figure 8.4(d)]. The various minima in this time interval were then expressed as fractions of the averaged interval. Typical calculations for the occurrence of the high velocity peaks in the crosscorrelated output, expressed in terms of fraction of the averaged RR interval, shown in Figure 8.4(d) are illustrated in **Worksheet 1.**

As mentioned earlier, it was observed that the interferometer signal reflects an upward motion of the target (i.e. a motion that decreases the distance between the transmitting antenna and the target) with a negative deflection in the time varying plots. In other words, any upward movement of the chest wall of a subject is seen as a negative deflection on the ordinate of the interferometer recording.

Figure 8.5(a - i) indicates by means of bar-graphs the distribution in the number of peaks in the crosscorrelated result as a function of age, height and weight of the subjects. These histograms were plotted in order to investigate if there is any relation between the number of peaks in a subject and the subject's age, height and

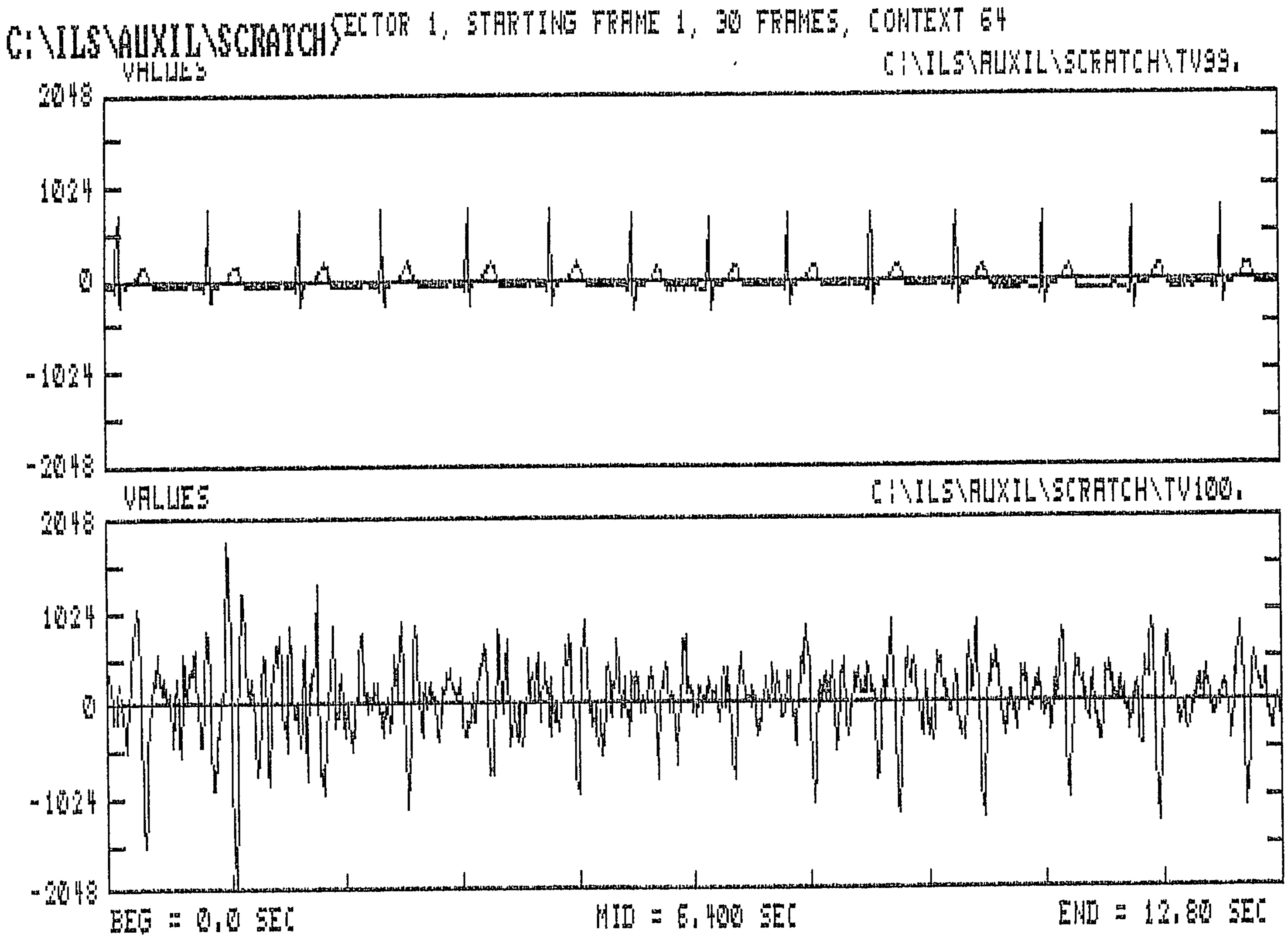


Figure 8.4(a). Digitized ECG recording from a male subject 26 years old, weighing 170 lbs, and 71 inches tall.

Figure 8.4(b). Digitized interferometer recording from the same male subject who is 26 years old weighing 170 lbs, and 71 inches tall.

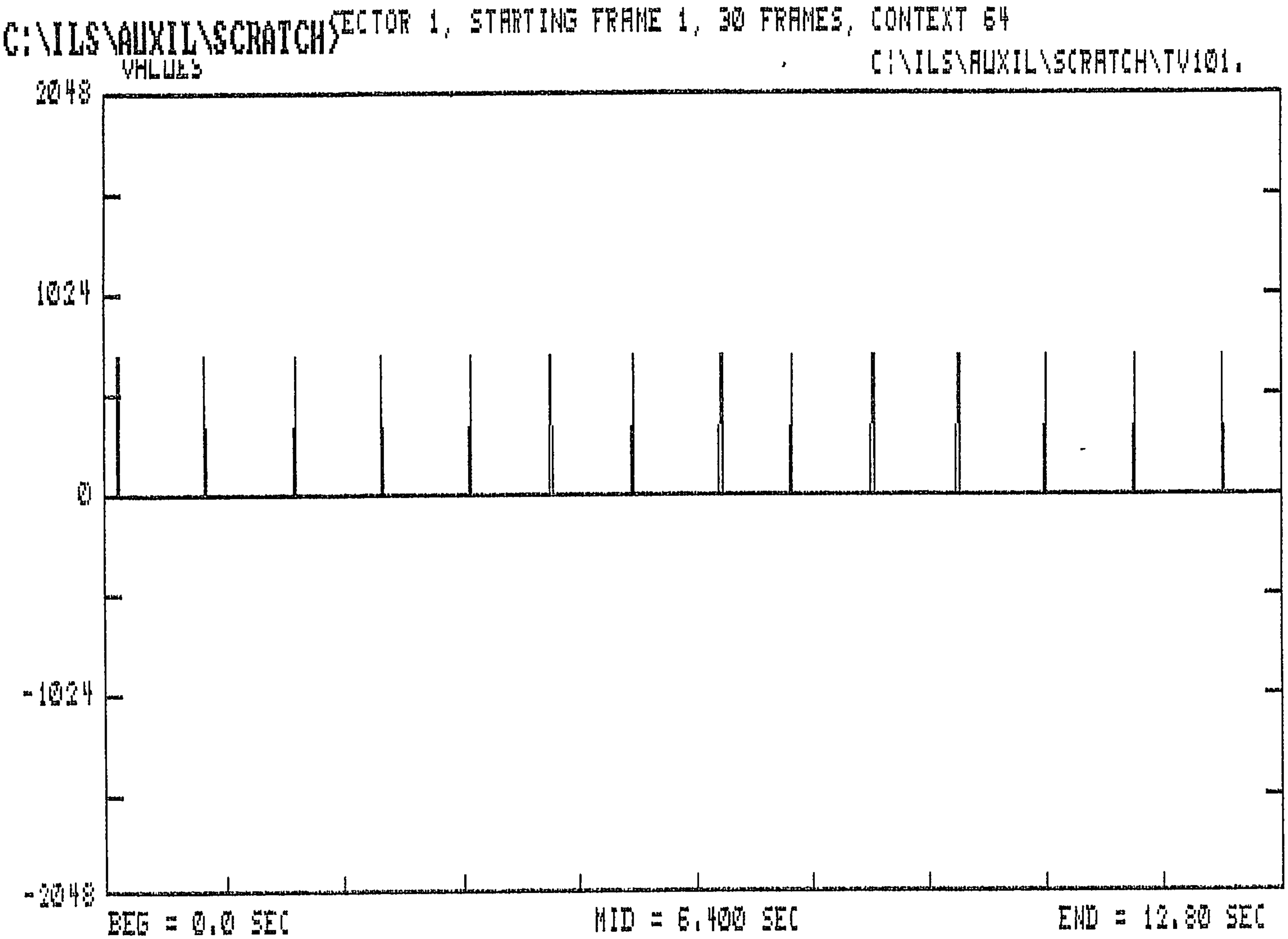


Figure 8.4(c). Digitized R wave pulse train obtained from the ECG in Fig.8.4(a) as described by the procedure in the section discussing signal processing.

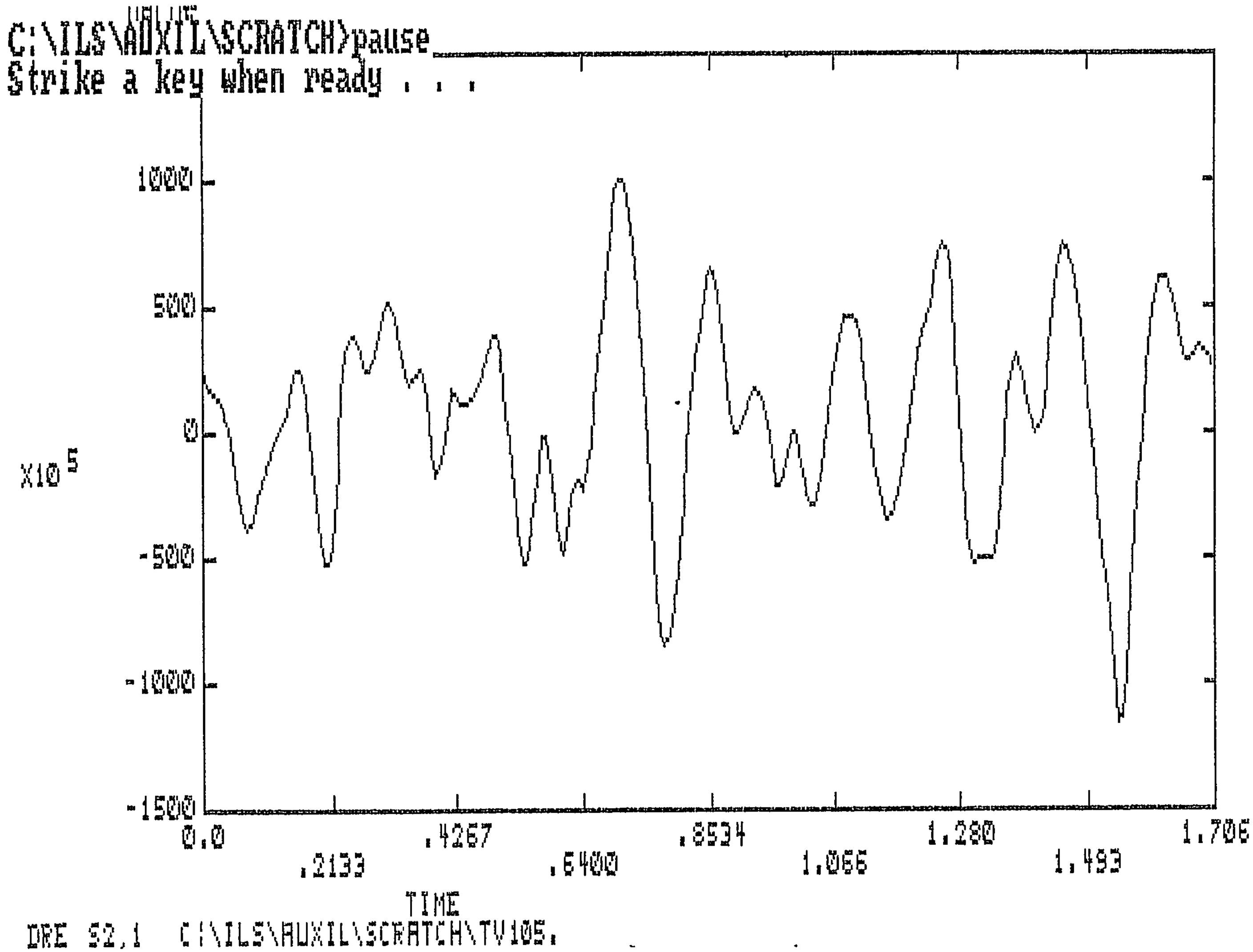


Figure 8.4(d). Result of crosscorrelating all 30 records of digitized interferometer data with 30 records of the ECG R wave pulse train from the male subject who is 26 years old, weighs 170 lbs, and is 71 inches tall.

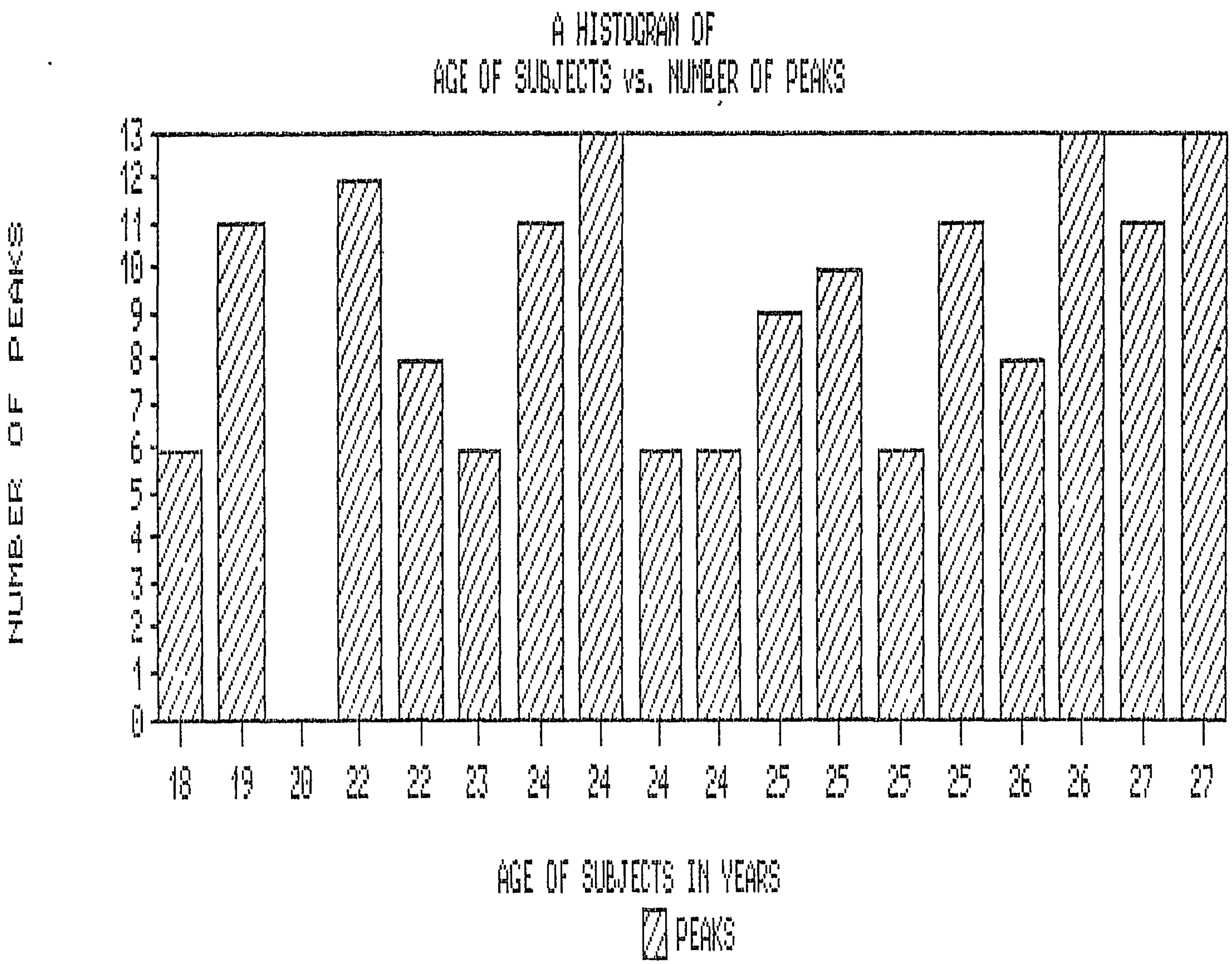

A HISTOGRAM OF
AGE OF SUBJECTS vs. NUMBER OF PEAKS
NUMBER OF PEAKS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
18
19
20
22
22
23
24
24
24
24
25
25
25
25
26
26
27
27
AGE OF SUBJECTS IN YEARS
PEAKS

Figure 8.5a

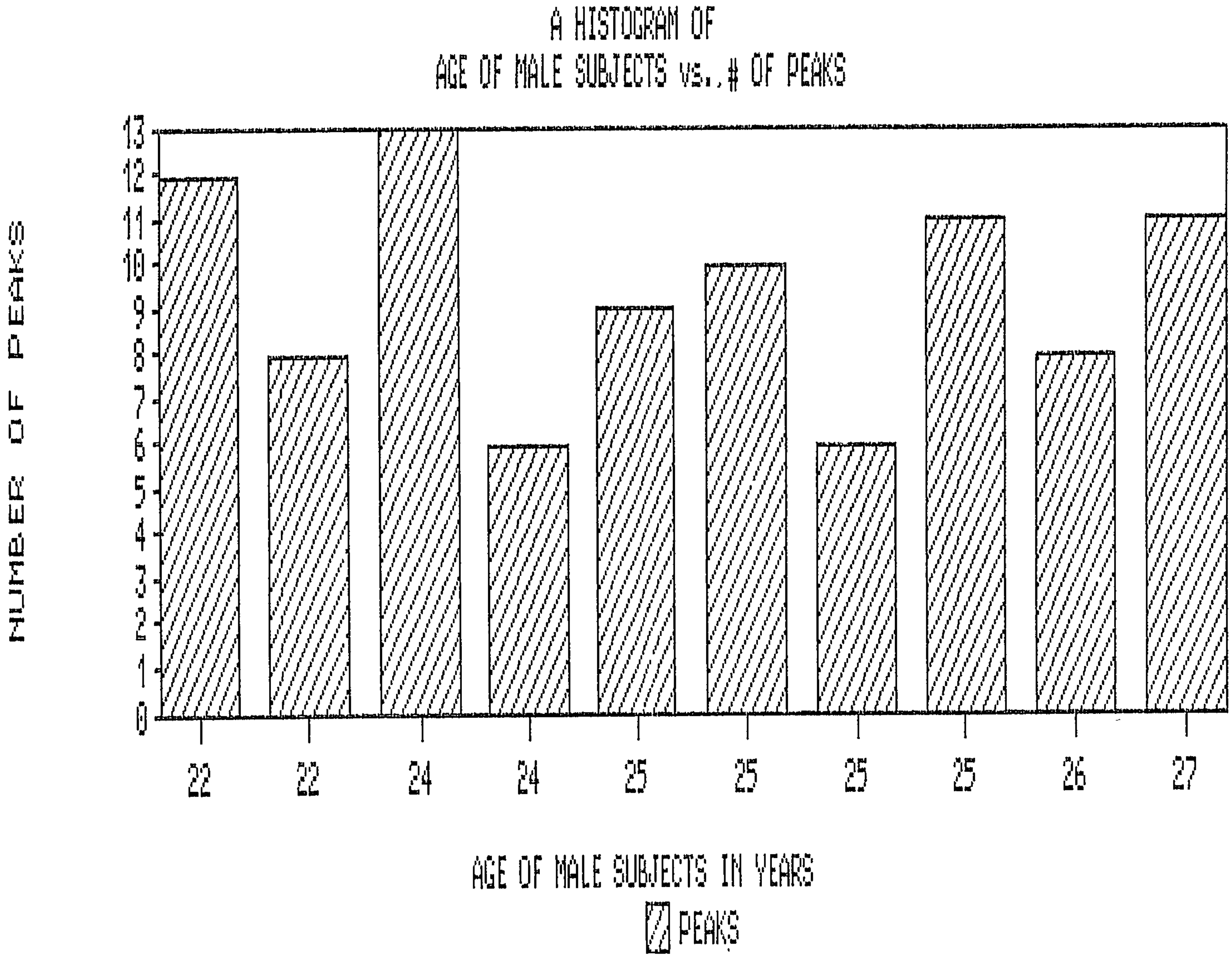

A HISTOGRAM OF
AGE OF MALE SUBJECTS vs.,# OF PEAKS
NUMBER OF PEAKS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
22
22
24
24
25
25
25
25
26
27
AGE OF MALE SUBJECTS IN YEARS
PEAKS

Figure 8.5b

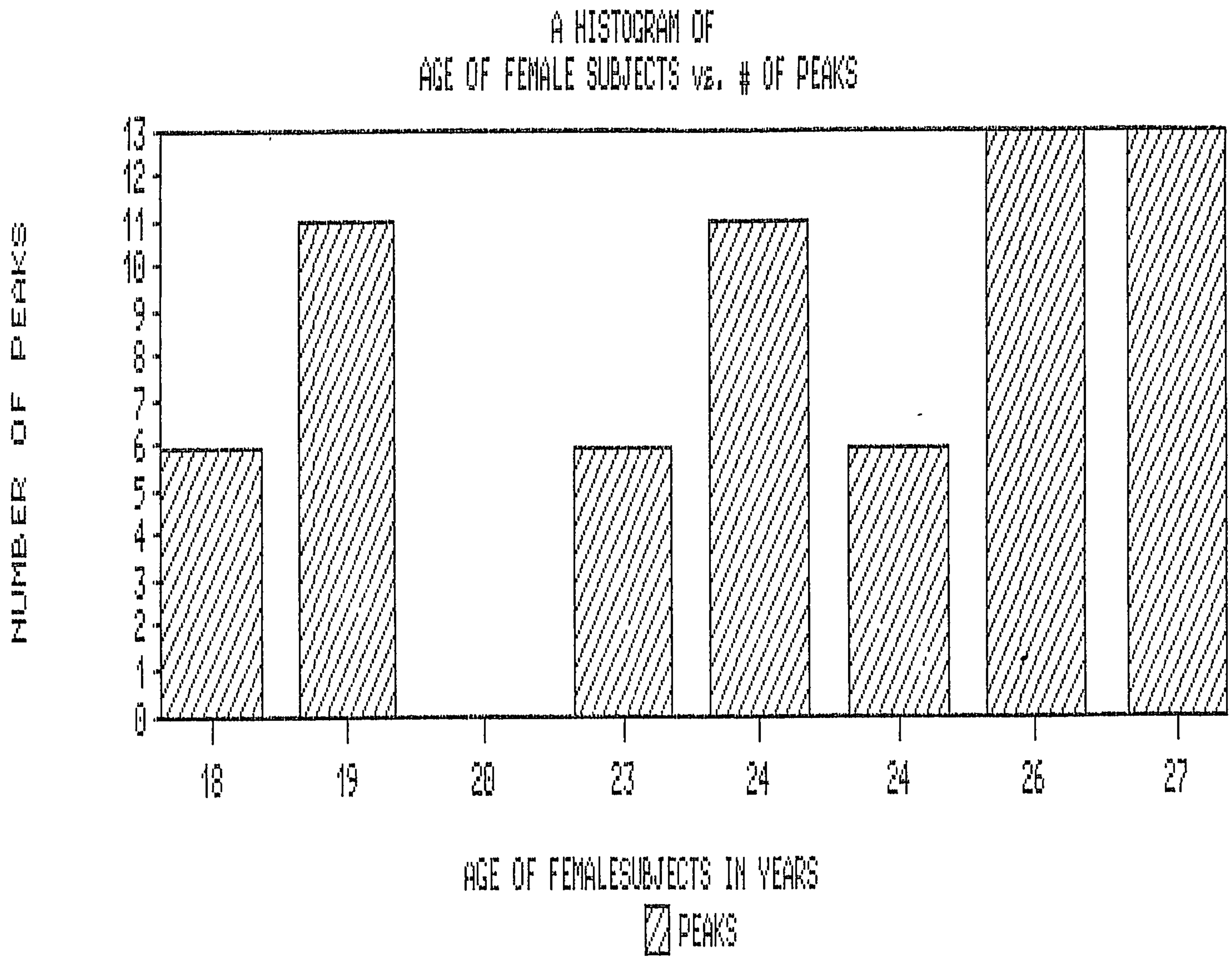

A HISTOGRAM OF
AGE OF FEMALE SUBJECTS vs. # OF PEAKS
NUMBER OF PEAKS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
18
19
20
23
24
24
26
27
AGE OF FEMALESUBJECTS IN YEARS
PEAKS

Figure 8.5c

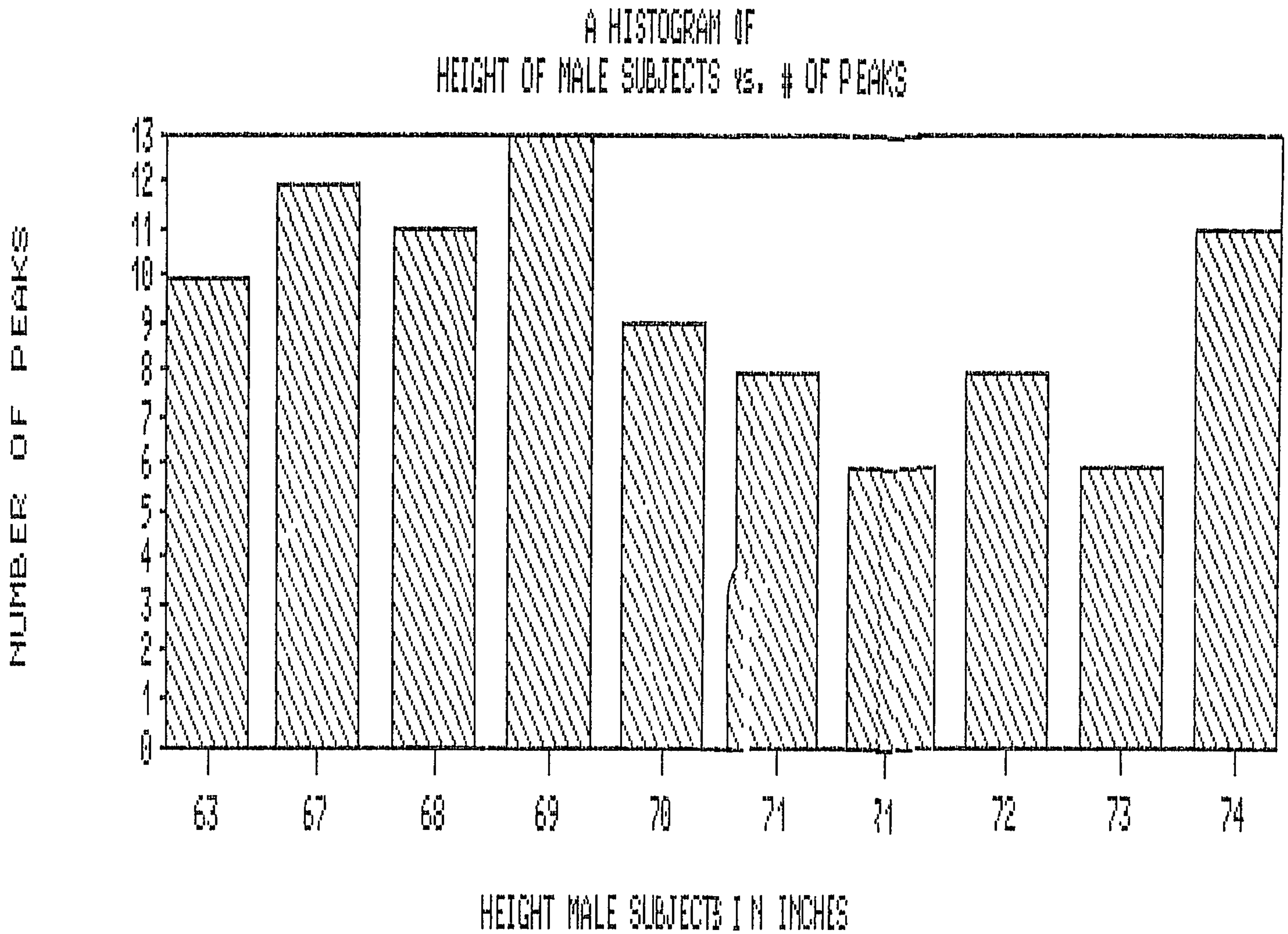

A HISTOGRAM OF
HEIGHT OF MALE SUBJECTS vs. # OF PEAKS
NUMBER OF PEAKS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
63
67
68
69
70
71
71
72
73
74
HEIGHT MALE SUBJECTS IN INCHES

Figure 8.5e

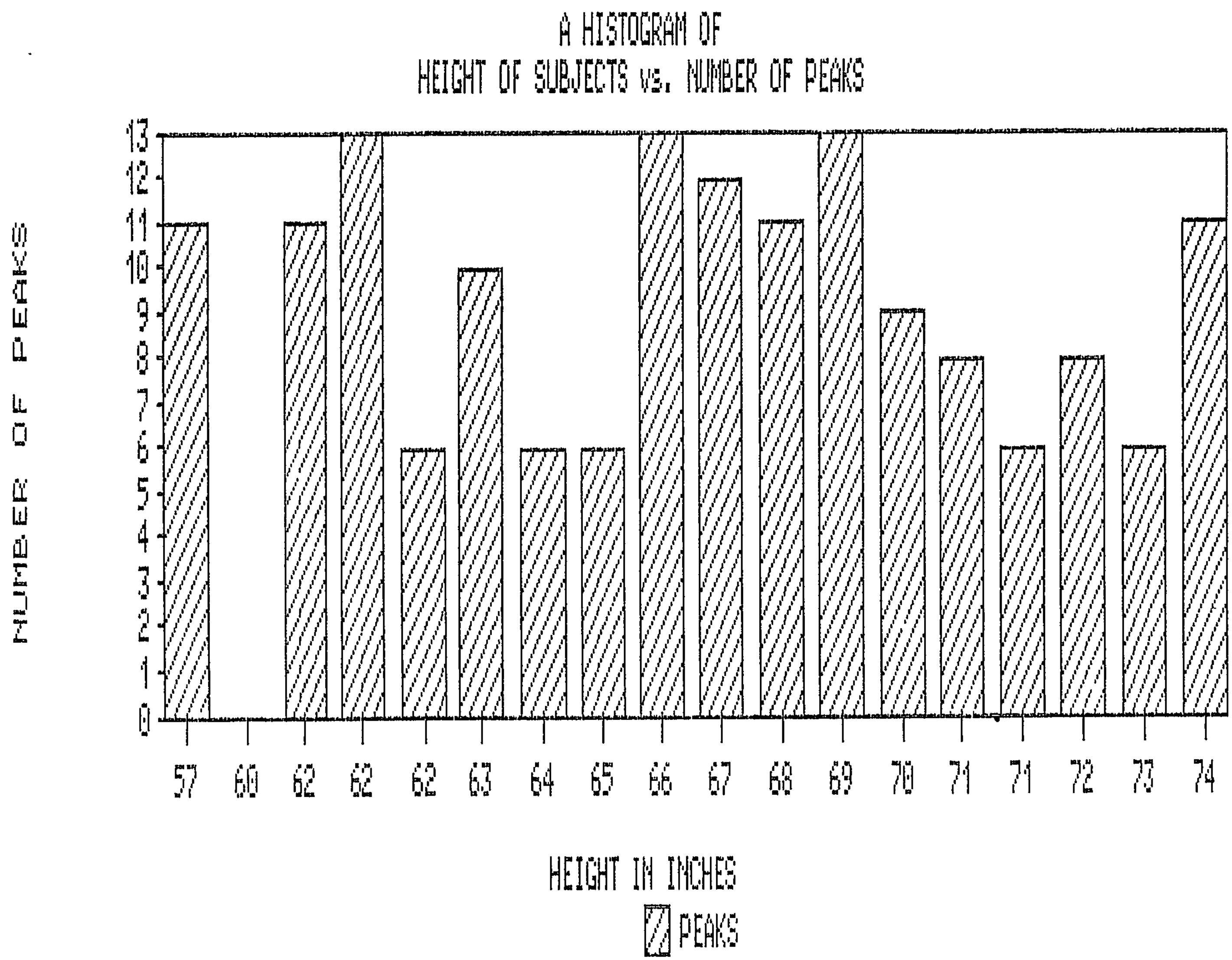

A HISTOGRAM OF
HEIGHT OF SUBJECTS vs. NUMBER OF PEAKS
NUMBER OF PEAKS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
57
60
62
62
62
63
64
65
66
67
68
69
70
71
71
72
73
74
HEIGHT IN INCHES
PEAKS

Figure 8.5d

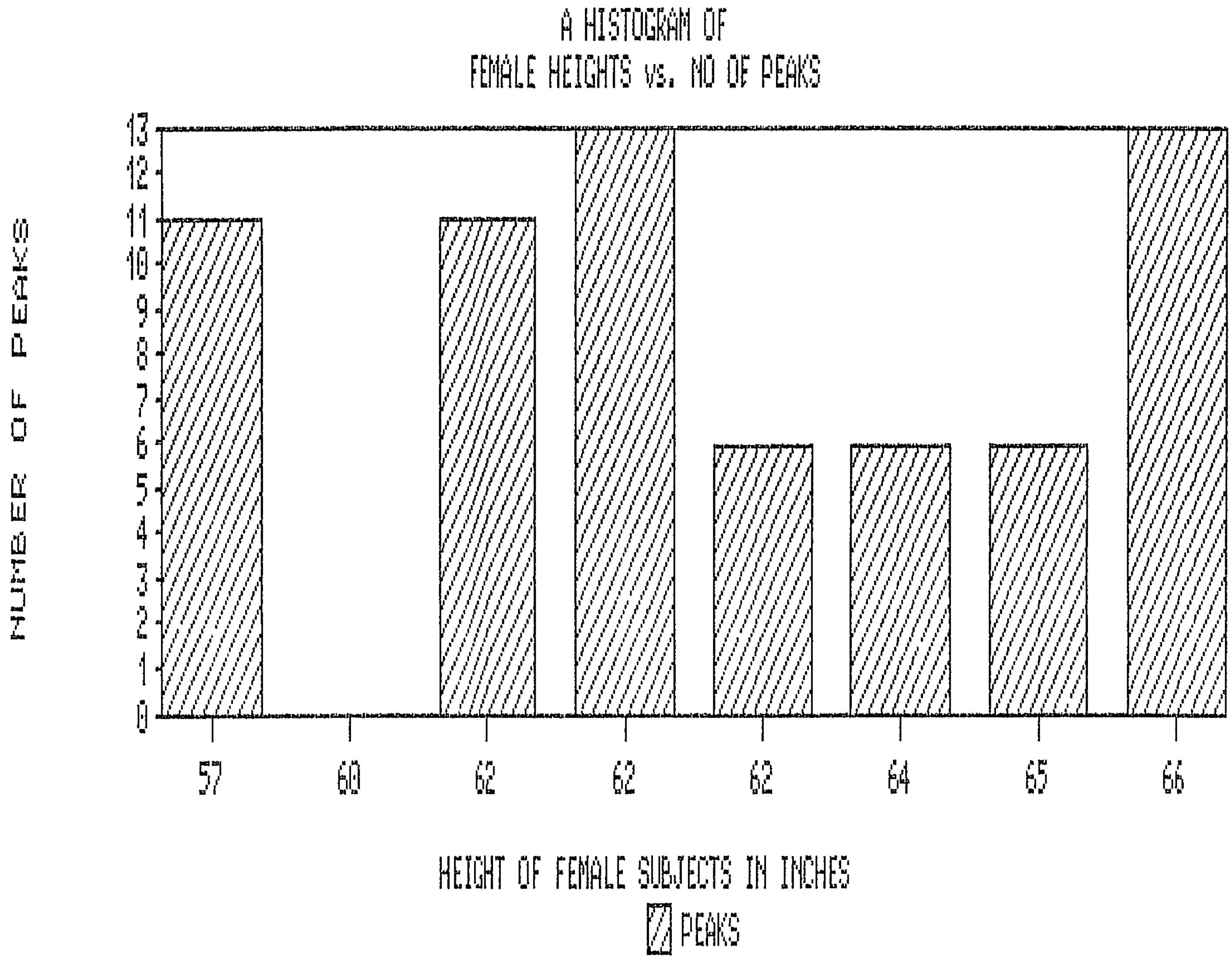

A HISTOGRAM OF
FEMALE HEIGHTS vs. NO OF PEAKS
NUMBER OF PEAKS
13
12
11
10
9
8
7
6
5
4
3
2
1
0
57
60
62
62
62
64
65
66
HEIGHT OF FEMALE SUBJECTS IN INCHES
PEAKS

Figure 8.5f

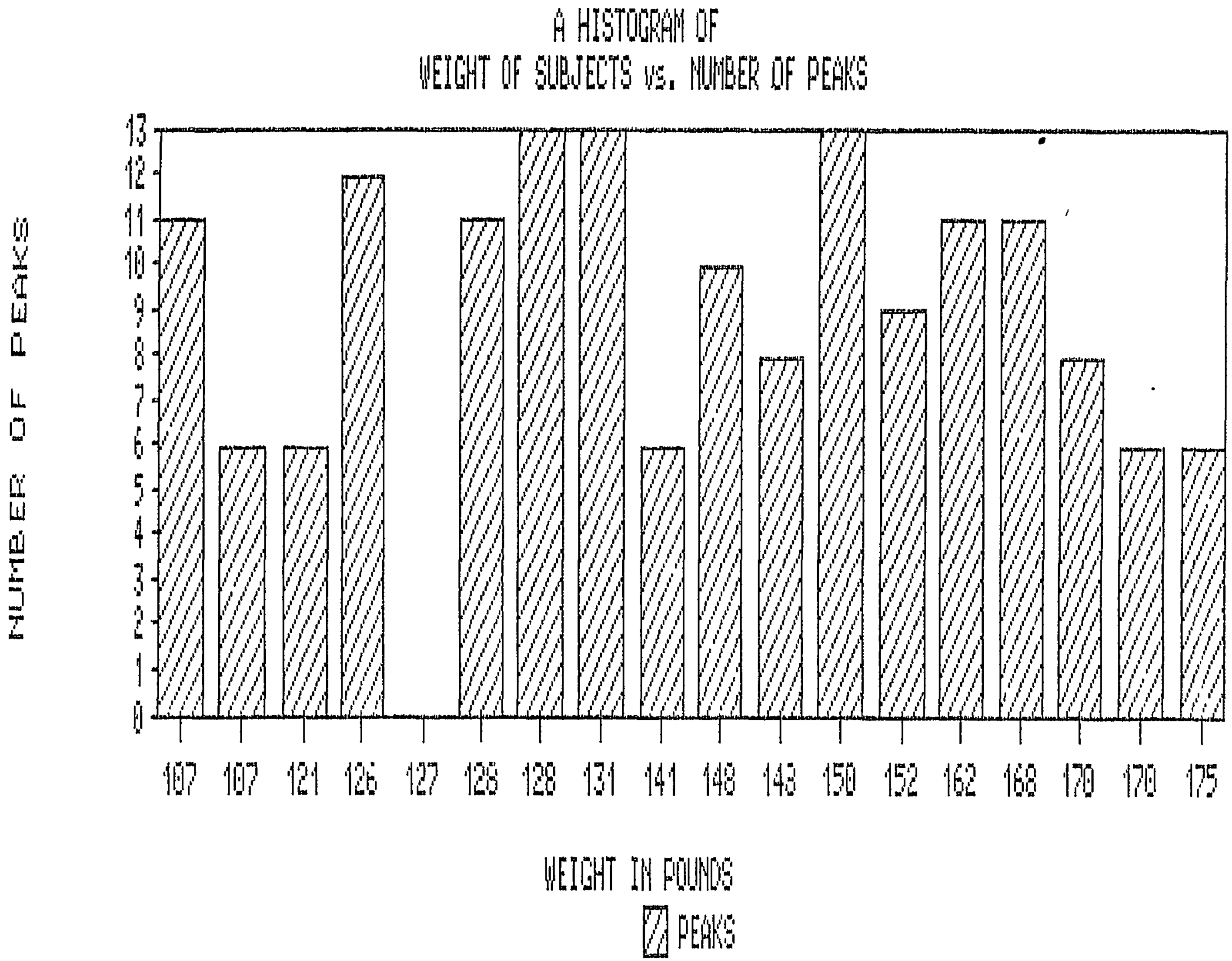

A HISTOGRAM OF
WEIGHT OF SUBJECTS vs. NUMBER OF PEAKS
NUMBER OF PEAKS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
107
107
121
126
127
128
128
131
141
148
143
150
152
162
168
170
170
175
WEIGHT IN POUNDS
PEAKS

Figure 8.5g

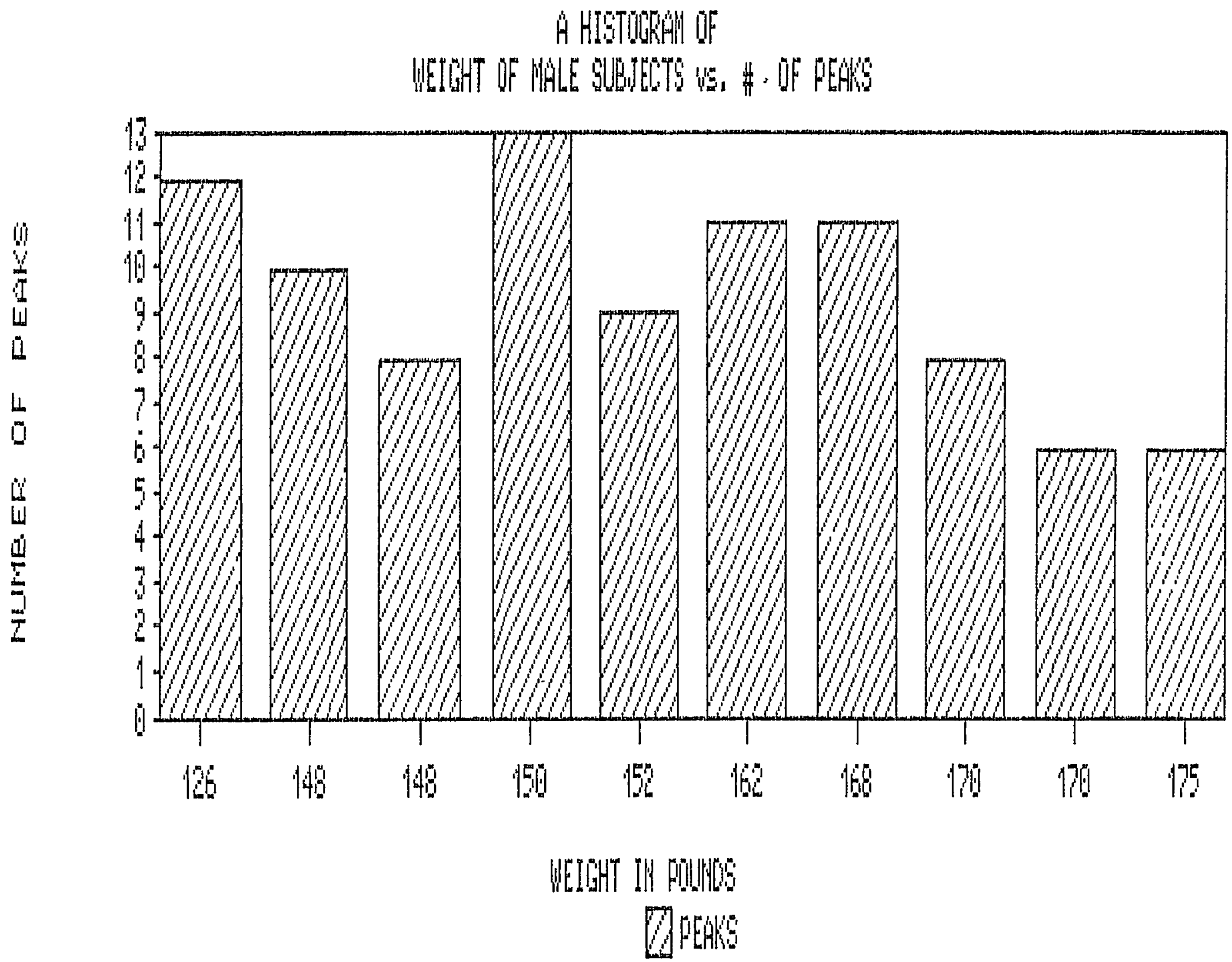
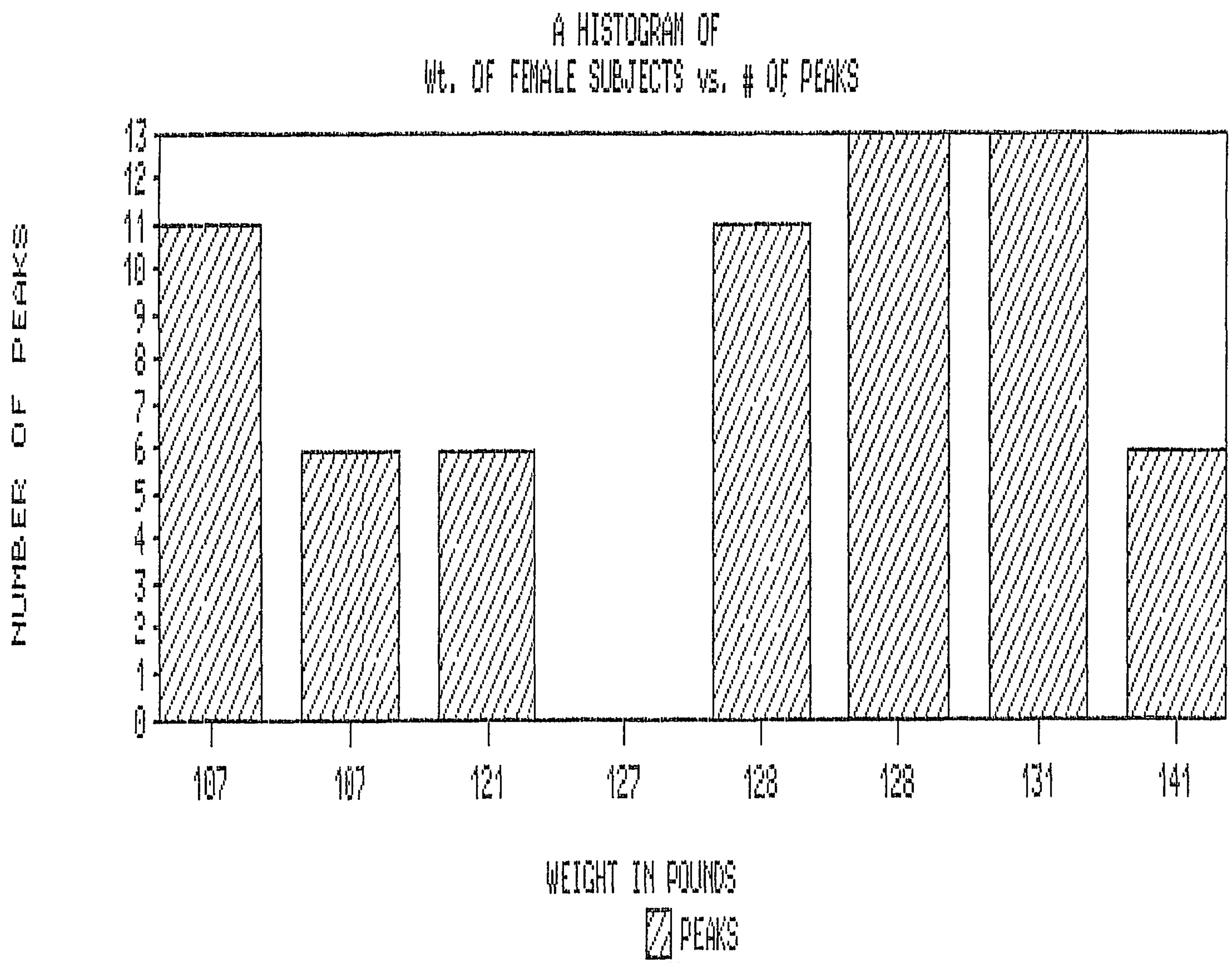

A HISTOGRAM OF
WEIGHT OF MALE SUBJECTS vs. # OF PEAKS
NUMBER OF PEAKS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
126
148
148
150
152
162
168
170
170
175
WEIGHT IN POUNDS
PEAKS

Figure 8.5h



A HISTOGRAM OF
Wt. OF FEMALE SUBJECTS vs. # OF PEAKS
NUMBER OF PEAKS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
107
107
121
127
128
128
131
141
WEIGHT IN POUNDS
PEAKS

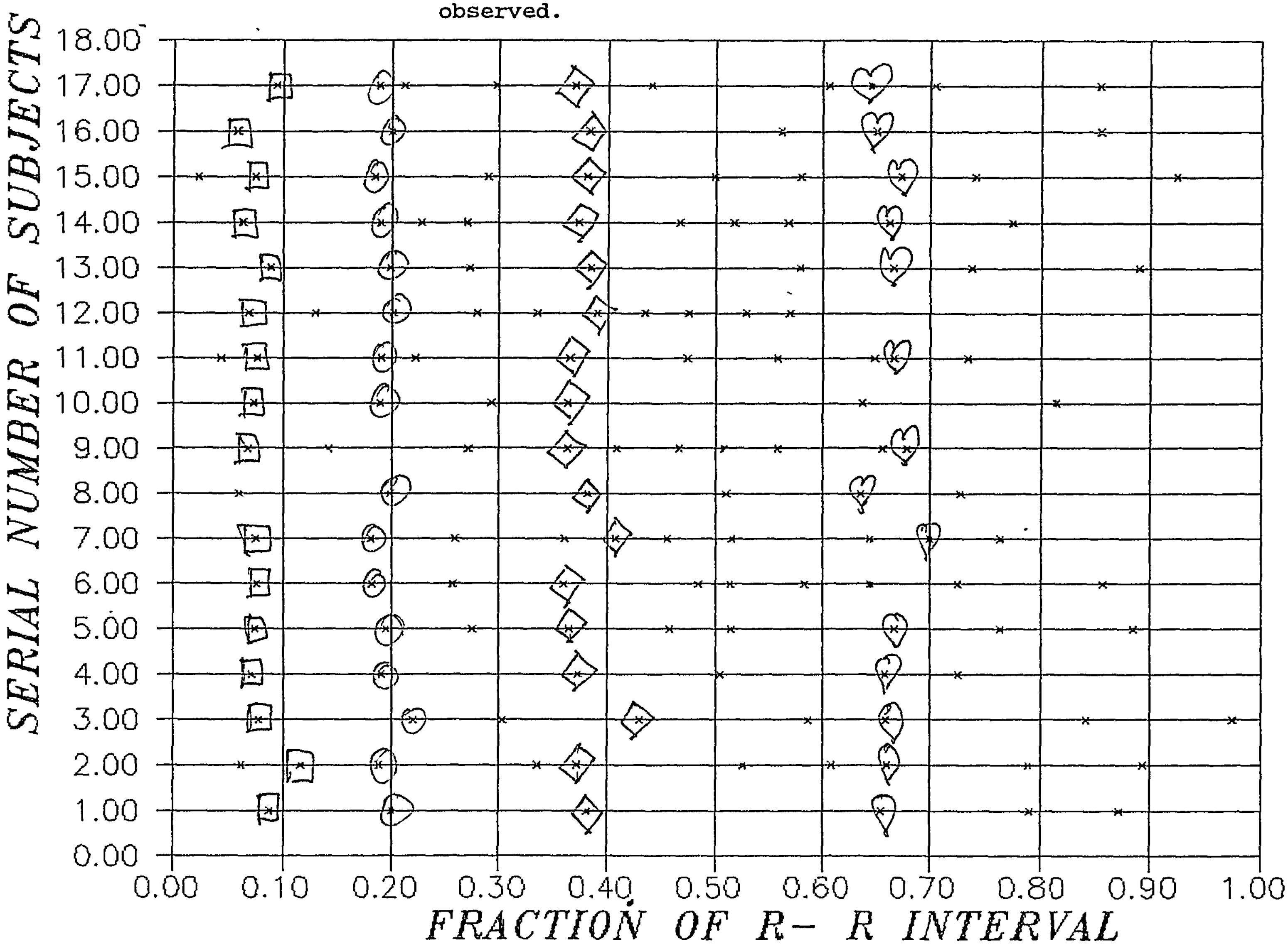
Figure 8.5i

age. No significant pattern, however, is observed. It may be interpreted therefore that the interferometer recordings are independant of factors like age, height, weight and sex.

8.3 PHYSIOLOGICAL INTERPRETATIONS

The crosscorrelated results such as one in Figure 8.4(d) need to be related to the mechanical events in the cardiac cycle. The ventricles eject their contents during the Q-T interval which occupies roughly the first third of the R - R interval. The scattergram, Figure 8.6 indicates the timing of peaks in each subject in terms of fraction of an R - R interval. Four distinct clusters of points are observed. The first two such clusters occur in the first quarter of the R - R interval. Consequently it may be hypothesized that the peaks contributing to this cluster which occur soon after the R wave are related to the rapid onset of ventricular ejection at the beginning of systole at which point the velocity of blood flow in the aorta is at its maximum. From ACG in Figure 5.3 we notice that the E peak of the ACG follows the R peak of the ECG. Also, the E peak occurs at approximately 0.12 RR. In our scattergram (Fig.8.6) we notice two clusters in the first quarter of the RR interval. The interpretation of the vibrational activity during the remaining R - R interval can only be speculated at this time. The vibrations late in the R - R interval may reflect atrial contraction; a second possibility is that the chest cavity is a mechanical resonator that is excited by the vigorous ventricular activity early in the R - R interval and the activity late in the R - R interval is a reflection of the *'ringing'* of the cavity. Also, as stated in our earlier discussion on Apexcardiography, the ACG has a distinct 'O' peak approximately halfway between the R-R interval. This 'O' peak represents the rapid ventricular filling following the isometric relaxation phase. In our crosscorrelated result a cluster of peaks is also observed between 0.35 and 0.40 RR.

Figure 8.6 This figure shows the distribution of the peaks observed in the crosscorrelated results of each of the 18 subjects in terms of fraction of the R-R interval. Four distinct clusters are observed.



8.4 RECOMMENDED FUTURE INVESTIGATIONS AND POTENTIAL APPLICATIONS

This technique of cardiopulmonary monitoring by means of a microwave interferometer has the unique advantage of not requiring any physical contact with a patient.

Future research ought to be aimed at developing additional filtering algorithms which would minimize spurious vibration signals. Also, attempt should be made to extend the crosscorrelation delay parameter τ over the entire 60 seconds of data which would perhaps smoothen out the final result further and reflect mechanical cardiac events more clearly and accurately.

Data collected from the eighteen subjects lying on their stomachs with their backs towards the transmitting antenna of the interferometer did not exhibit an periodicity with reference to the ECG recordings. Two such sets of data are shown in figure 8.7(a,b). Further investigation needs to be conducted in this direction. The database presently available need to be expanded and children should also be included as subjects in future experiments. It may be possible to detect holes in the wall separating the right and left hearts in infants and children (Atrial and Ventricular septal defects). If possible, data should be collected from subjects with known cardiac diseases. Comparative study between data collected from normal, healthy subjects and those from subjects with heart diseases may divulge valuable information.

To make the instrument portable, the entire interferometer should be redesigned and constructed using modern electronic technology. Solid-state components for a modern instrument are being designed at NJIT as of this writing.

The results obtained from the experiments performed on the microwave interferometer are extremely encouraging. The instrument may prove to have useful application for monitoring the critically ill cardiac patient. As stated a earlier, the instrument could prove useful as a coarse screening device for detecting gross cardiac abnormalities such as septal defects in infants and children. It may be useful in neonatal intensive care unit to monitor infants susceptible to sudden infant death syndrome (SIDS or '*crib death*'), and to monitor the cardiopulmonary rhythm of severely burned patients to whom electrodes cannot be safely attached.

Appendix (A)

The various programs that have been used to perform data processing, data manipulation and signal processing of the signals obtained from the microwave interferometer and the ECG are listed in this appendix.

APPENDIX A(1)

This batchfile is required to be run at the beginning of each session to set up the working environment of ILS-IEEE. The ILS command ILS C is also executed as a part of this program which initialises the ILS COMMON file CM9999.

```
------------------------------------------------------------
-
                 ;BATCHFILE  :  AUTOEXEC.BAT
;-----------------------------------------------------------
-PATH C:\ILS;C:\ILS\AUXIL\TANMOY;C:\WORD;C:\DOS;C:\TURBO;
PROMPT $P$G
ILSBOOT1
ILSBOOT2
cd ils\auxil\scratch
ils c
------------------------------------------------------------
-
```

APPENDIX A(2)

The program DATAACQ.BAS, written in BASIC, that performs data acquisition is listed here. With the signals from the interferometer and the ECG given as input to the channels ZERO and ONE of the DASH-16 A/D converter, this program is RUN after invoking GWBASIC.

```
100
'**********************************************************
110 '*
*
120 '*     DATAACQ.BAS   :  SAMPLE DATA  FROM TWO CHANNEL
*
130 '*                                          11-27-87
*
140
'**********************************************************
150 '
160 '--------------- STEP 1  ------------------------------
-
170 'Load DASH16.BIN by contracting workspace  & initialize
175 '-------------------------------------------------------
-
180 CLEAR, 49152!       'Contract BASIC's workspace to 48K
190 DEF SEG = 0         'Get BASIC's segment in memory
200 SG = 256 * PEEK(&H511) + PEEK(&H510)
210 SG = SG + 49152!/16
```

```
220 DEF SEG = SG        'Load segment for CALL routine
230 BLOAD "DASH16.BIN", 0        'Load it
240 DIM DIO%(8),A%(20000)        'Initialize data arrays
250 DIO%(0) = &H300 'DASH-16 board base address
260 DIO%(1) = 2     'Selected interrupt level for DASH-16
270 DIO%(2) = 3     'Selected DMA level for DASH-16
280 DASH16 = 0      'Declare & initialize other CALL
parameters
290 FLAG% = 0
300 MD% = 0         'Select Mode 0 - initialize driver
310 CALL DASH16 (MD%, DIO%(0),FLAG%)   'do it
320 IF FLAG%<>0 THEN PRINT "INITIALIZATION ERROR":STOP  'any
errors?
330 '
340 '--------------- STEP 2 --------------------------------
350 ' Prompt user for multiplexer scan limits
360 ' (this step can be omitted if default limits o.k.)
370 ' Set up multiplexer scanning limits
375 '-------------------------------------------------------
380 MD%=1           'Mode 1 - set scan limits
390 INPUT "Lower multiplexer scanning limit (0-7 or 15)? :
",DIO%(0)
400 INPUT "Upper multiplexer scanning limit (0-7 or 15)? :
",DIO%(1)
410 CALL DASH16 (MD%, DIO%(0),FLAG%)
420 IF FLAG%<>0 THEN PRINT "Error in scan limits # ";FLAG% :
STOP
```

```
430 '
440 '--------------- STEP 3 -------------------------------
-
450 ' Set up SAMPLE   rate ( 400Hz = 1,000,000 /2500 )
451 ' for two channels, so each channel has 200 Hz sampling
452 ' rate
455 '-----------------------------------------------------
460 MD% = 17
470 DIO%(0) = 25  : DIO%(1) = 100
480 CALL DASH16 (MD%, DIO%(0),FLAG%)
490 IF FLAG%<>0 THEN PRINT"Error in scan rate set up #
";FLAG% : STOP
500 '
510 '--------------- STEP 4 -------------------------------
-
520 ' Do 20000 conversions into array A%(*) using mode 4
521 '-----------------------------------------------------
-
530 DIO%(0) = 20000          'Number of conversions
535 XX=DIO%(0)
540 DIO%(1) = VARPTR(A%(0))   'Array locator
550 DIO%(2) = 1               'Trigger source - programmable
timer
560 MD%=4
570 CALL DASH16 (MD%, DIO%(0),FLAG%)
580 IF FLAG%<>0 THEN PRINT "Error in mode 4 # ";FLAG% : STOP
590 '
```

```
600
'==========================================================
610 '<<  default ::  create  a  data  file with  name :
>>
612 '<<  ( HO10 ) -line  690
>>
620 '<<  ALL DATA ARRAY IS ASSIGN TO A%( 20000 )  PTS
>>
630 '<<  WE CAN CHANGE ===> ( Line 240 , 530 )
>>
632 '<<  TO SET MORE  DATA ARRAY
>>
640 '<<  THEN CHANGE LINE 648 for # of frames
>>
645 '<<  ==  DEFAULT 31 FRAMES picture
>>
650 '-------------------------------------------------------
-
660 CLS : PRINT:PRINT:PRINT " ( 1 )  Show  the  input
signal  "  :PRINT
670 PRINT " ( 2 )  Show  the  input  signal  and  save  it
in  file EG10 "
680 PRINT: PRINT " ( 3 )  Save  data  in  file  EG10  only
"
690  FILE$ = "HO10"   : '***  CREATE A FILE  ----EG10----
700  INPUT T : IF T>3 THEN 700
710  ON T  GOTO 730, 840 ,990
```

```
720 '-----------------------------------------------------
722 '  Plot signal on screen
724 '-----------------------------------------------------
730  CLS :SCREEN 2 : LINE (640,101)-(0,101)
740  FOR J = 1 TO 32
750     LOCATE 1,1 : PRINT J
760      FOR NN=1 TO 640
770          N=NN+640*(J-1)
780          A%(N)=(-A%(N)+2048)/20
785  IF (N>=XX) GOTO 830
790          LINE -(NN,A%(N))
800      NEXT NN
810     CLS : LINE (640,101)-(0,101)
820   NEXT J
830  PRINT "!!!!! TOTAL # OF SAMPLED DATA"; N  : END
840 '----------------------------------------------------
842 '  Plot signal and save in file HO10
844 '----------------------------------------------------
850  OPEN FILE$ FOR OUTPUT AS #2    'CREATE FILE NAME HO10'
860  CLS :SCREEN 2 : LINE (640,101)-(0,101)
870  FOR J = 1 TO 32
880     LOCATE 1,1 : PRINT J
890      FOR NN=1 TO 640
900          N=NN+640*(J-1)
910       PRINT #2,A%(N)     :'========SAVE DATA
920          A%(N)=(-A%(N)+2048)/20
930          LINE -(NN,A%(N))
```

```
935  IF (N>=XX) GOTO 830
940      NEXT NN
950    CLS : LINE (640,101)-(0,101)
960  NEXT J
970  CLOSE
980 END
990  '-----------------------------------------------------
992  '   Save data
994  '-----------------------------------------------------
1000 OPEN FILE$ FOR OUTPUT AS #2    'CREATE FILE NAME HO10'
1010 PRINT " -------  Data   File  is  " FILE$ "  ----------
"
1020  FOR  I=1 TO DIO%(0)
1030       PRINT #2,A%(I)
1040       NEXT I
1050  CLOSE
1060 END
1070 '=====================================================
```

APPENDIX A(3)

The source code of the program TANMOY.EXE is listed here. This program, written in the high level language C, separates the two channels of input data that is acquired by DATAACQ.BAS. The separated data are stored in ASCII code in two different files whose names are given by the user.

For example keying in:

TANMOY TWO_CHAN_DATA CHAN_1 CHAN_2

will take TWO_CHAN_DATA as the input, separate the data and store them in the files CHAN_1 and CHAN_2.

```
/*=====================================================*/
/*    File name :  TANMOY.C                            */
/*    This program seperate two channels data which is */
/*    in ASCII code                                    */
/*=====================================================*/

#include "stdio.h"

FILE  *IN, *CH1,  *CH2 ;

main (argc,fname)
int argc;
char *fname[];
{
  unsigned int   tcnt=0, cnt1=0, cnt2=0 ;
```

```
  int fg= 1, data, t, tog;


  if ( argc != 4 )
  {
   printf("\n\n !!!! Seperate  File  Command Format :\n\n
");
   printf(" TANMOY  In_Data_file  Out_CH1_file  Out_CH2_file
\n");
    exit(1);
  }
  IN  = fopen( fname[1], "r" );
                                   /* assign original data file */
    if ( IN == NULL )
     {
      printf("\n\t****  Can't  open  file: %s
\n",fname[1]);
      exit(0);
     }
  CH1 = fopen( fname[2], "w" );
                                  /* assign channel 1 data file */
    if ( CH1 == NULL )
     {
      printf("\n\t****  Can't  open  file: %s \n",fname[2]
);
      exit(0);
     }
  CH2 = fopen( fname[3], "w" );
```

```
/* assign channel 2 data file  */
```

```
  if ( CH2 == NULL )
     {
      printf("\n\t****  Can't  open  file: %s \n",fname[3]
);
      exit(0);
     }
/*----------------------------------------------------------
*/
printf("!!!!! Start .......Please wait\n");
  tog = 0;
  while( fg )
  {
     t = fscanf( IN,"%d", &data);
                    /* Input from ASCII integer data file  */
     if ( t== EOF )   fg=0;                           /* EOF */
       else
      {
         tcnt++ ;
         if ( tog==0 )
           {
              fprintf( CH1,"%d\n", data);
              tog= 1;
              cnt1++;
            }
           else
            {
               fprintf( CH2,"%d\n", data);
```

```
              tog= 0;
              cnt2++;
            }
      }
  } /* end of while */
 fclose(IN);    fclose(CH1);    fclose(CH2);

 printf("\n Original  Data file= %s  has %d  data
points.\n",
                                fname[1],tcnt);
 printf("\n Channel 1 Data file= %s  has %d  data
points.\n",
                                fname[2],cnt1);
 printf("\n Cnannel 2 Data file= %s  has %d  data
points.\n",
                                fname[3],cnt2);
}   /* enf of main */
/*-------------------------------------------------------*/
```

APPENDIX A(4)

The program BASU1.PAS, written in the high level language Pascal, takes the raw digitized ECG signal (which is one of the ASCII coded output files of TANMOY.EXE) as input. Given a threshold value it substitutes a zero for all signal values below the threshold and maintains other values as they are. As a result, the output is a train of pulses which represent the R waves of the ECG.

```
************************************************************
            PROGRAM BASU1.PAS FOR R WAVE DETECTION
***********************************************************
program sort;
Var
   A : Integer;
   Filein,Fileout : text;
   Filename,Namefile : String[10];

Begin
     ClrScr;
     Writeln('Please Specify Name of File containing Data :
');
     Writeln('Note : Do Not attach any extension since the
program');
     Write('automatically attaches the ext ".DAT"  :  ');
     Readln(Filename);
     Namefile := Filename + '.OUT';
```

```
   Filename := Filename + '.DAT';
   Assign(Filein,Filename);
   Reset(Filein);
   Assign(Fileout,Namefile);
   Rewrite(Fileout);


   While not EOF(Filein) Do
   Begin
        Readln(Filein,A);
        Writeln(A);
        If A >= 250 { this is the value that an user has
                      to change to select different
                      thresholds; e.g. to choose a
                      threshold of 500, this statement
                      should be modified to read
                      " If A >= 500" }
          Then Writeln(Fileout,A)
          Else Writeln(Fileout,0);
   End;

   Close(Filein);
   Close(Fileout);
End. {Main}
```

APPENDIX A(5)

The program CONVERT.EXE converts integer ASCII coded data files into ILS-IEEE compatible data format which can be processed by the ILS-IEEE software. This program is equivalent to the ILS-IEEE command WRT in the ILS-PC1 (Commercial Version)

```
/*==========================================================*
/
/*   File Name : CONVERT.C
*/
/*==========================================================*
/
#include "stdio.h"
#define  BIN_MODE  0
#define  ASC_MODE  1

FILE *gfopen();
FILE  *in1, *in2,  *out ;

main (argc,name)
int argc;
char *name[];

{
  char  code11, code22, ch;
  int   t, nb ;
```

```
  long  ctr, p ;

  if ( argc != 4 )
  {
    printf ("!Command Format :\n\n\n ");
    printf (" CONVERT  In_Data_file   In_Head_file
                Output_file    \n");
    exit(1);
  }

  printf ("\n\n");
  printf ("\n------  Default  Data  Points transfered  is  :
                        15,000  \n");
  printf ("\n------  Do  You  Want  Change  the
Number?\n");
  printf ("\n------  Type  ( Y )  to  confirm  /OR/   RET
to
                        default  ");

  p = 15000*2 ;
/*-------------------------------------------------------*/
/* Each One data is translated to two bytes, p is counter */
/*-------------------------------------------------------*/
  scanf  ("%c",&ch);
  if ( ch == 'y' ||  ch == 'Y' )
    {
       printf (" \n!!!!!   Input  Bytes  Number ==   ");
```

```
        scanf ("%ld",&p);  p=p*2;   printf ("#### %ld",p);
      }
  in1 = gfopen( name[1], "r", ASC_MODE );
                                     /* assign data file  */
  in2 = gfopen( name[2], "r", BIN_MODE );
                                    /* assign head file  */
  out = gfopen( name[3], "w", BIN_MODE );
                                    /*     output  file  */

  if ( (in1 == NULL || in2 == NULL  || out == NULL) )
     {
       printf(" \n\t****  Can't  open  a  file  **** \n");
       exit(0);
     }
  /*--------------------------------------------------------
*/
  /* create the header file for each ILS-IEEE data file
*/
  /*   STEP 1
*/
  /* : copy 512  bytes from header file  to output  file
*/
  /*--------------------------------------------------------
*/

  for ( ctr = 1;  ctr <= 512 ;  ctr++ )
      {
```

```
            ch = getc(in2);
            putc (ch,out) ;
        }
    fclose(in2);
    ctr=0;  /* reset counter value  */

    /*-------------------------------------------------------
*/
    /*  STEP 2 :: copy the transleted ILS bin-code to output
*/
    /*   file
*/
    /*-------------------------------------------------------
*/

    t = fscanf(in1,"%d",&nb);
                    /*    input from integer data file
*/

    while ( t > 0 )           /*   check end of file   EOF
*/
      {
       code_trans (&code11, &code22, &nb);
       putc (code11,out);
       putc (code22,out);          /*   store HEX data   */
       ctr = ctr+2 ;
       t = fscanf(in1,"%d",&nb);
```

```
    }
  fclose(in1);

 /*----------------------------------------------------------
*/
 /*  Step 3 : copy remain data  to output file
*/
 /*----------------------------------------------------------
*/

  code11 = '\263' ;
  code22 = '\273' ;                  /* code B3 BB == 00 */

  while ( ctr < p )
     {
          putc (code11,out);
          putc (code22,out);
          ctr=ctr+2 ;
     }
  fclose(out);
  printf(" \n %ld  Bytes  translated \n",ctr );
}


/*-----------------------------------------------------------
*/
```

```
/*  this program  converts integer data file  which  is
*/
/*  created by A/D  converter under  MS-DOS into ILS-IEEE
*/
/*  compatible  data  format and RUNing under the ILS-IEEE
*/
/*  command language.
*/
/*----------------------------------------------------------
*/

code_trans (code1,code2,n)
char *code1, *code2 ;
int  *n;

  {
     char  fmsb, flsb;
     int   bk, sbk, x, y, nn;

/*----------------------------------------------------------
*/
/*     code transfer by assign 2 major block
*/
/* 0--1023---1024--2048,  (-1)---(-1024)--(-1025)--(-2048)
*/
/*----------------------------------------------------------
*/
```

```
if ( *n >= 0  &&  *n < 2048 )
  {
    bk = *n/256 ;   /* code is assibned by OCTAL nu.
*/

    switch (bk)
      {
        case '\000' : *code1 = '\263' ;
                        break ;   /* 0= hex B3 */
        case '\001' : *code1 = '\262' ;
                        break ;   /* 1= hex B2 */
        case '\002' : *code1 = '\261' ;
                        break ;   /* 2= hex B1 */
        case '\003' : *code1 = '\260' ;
                        break ;   /* 3= hex B0 */
        case '\004' : *code1 = '\267' ;
                        break ;   /* 4= hex B7 */
        case '\005' : *code1 = '\266' ;
                        break ;   /* 5= hex B6 */
        case '\006' : *code1 = '\265' ;
                        break ;   /* 6= hex B5 */
        case '\007' : *code1 = '\264' ;
                        break ;   /* 7= hex B4 */
      }          /*  first block 1st byte conver.  */
                /*    convert  2nd byte            */
```

```
        sbk = *n - bk*256 ;
/*      small  block  range  is  0---255                  */

       x = sbk/16 ;      /*  find  first 4 MSb in code2   */

        switch (x)       /*  256/16 = 16 ------ ( 0-15 )  */
          {
             case '\000' : fmsb = '\260' ;
                           break ;   /* 0= hex B0 */
             case '\001' : fmsb = '\240' ;
                           break ;   /* 1= hex A0 */
             case '\002' : fmsb = '\220' ;
                           break ;   /* 2= hex 90 */
             case '\003' : fmsb = '\200' ;
                           break ;   /* 3= hex 80 */

             case '\004' : fmsb = '\360' ;
                           break ;   /* 4= hex F0 */
             case '\005' : fmsb = '\340' ;
                           break ;   /* 5= hex E0 */
             case '\006' : fmsb = '\320' ;
                           break ;   /* 6= hex D0 */
             case '\007' : fmsb = '\300' ;
                           break ;   /* 7= hex C0 */

             case '\010' :  fmsb = '\060' ;
                            break ;  /* 8= hex 30 */
```

```
        case '\011' :  fmsb = '\040' ;
                       break ;  /* 9= hex 20 */
        case '\012' :  fmsb = '\020' ;
                       break ;  /* 10=hex 10 */
        case '\013' :  fmsb = '\000' ;
                       break ;  /* 11=hex 00 */

        case '\014' :  fmsb = '\160' ;
                       break ;  /* 12=hex 70 */
        case '\015' :  fmsb = '\140' ;
                       break ;  /* 13=hex 60 */
        case '\016' :  fmsb = '\120' ;
                       break ;  /* 14=hex 50 */
        case '\017' :  fmsb = '\100' ;
                       break ;  /* 15=hex 40 */
    }

y = sbk%16;        /*   find  4  LSB  in  code2    */

switch (y)         /*  256/16 = 16 ------ ( 0-15 ) */
  {
      case '\000' : flsb = '\013' ;
                    break ;     /* hex 0B */
      case '\001' : flsb = '\012' ;
                    break ;     /* hex 0A */
      case '\002' : flsb = '\011' ;
                    break ;     /* hex 09 */
```

```
case '\003' : flsb = '\010' ;
              break ;     /* hex 08 */

case '\004' : flsb = '\017' ;
              break ;     /* hex 0F */
case '\005' : flsb = '\016' ;
              break ;     /* hex 0E */
case '\006' : flsb = '\015' ;
              break ;     /* hex 0D */
case '\007' : flsb = '\014' ;
              break ;     /* hex 0C */

case '\010' :  flsb = '\003' ;
               break ;    /* hex 03 */
case '\011' :  flsb = '\002' ;
               break ;    /* hex 02 */
case '\012' :  flsb = '\001' ;
               break ;    /* hex 01 */
case '\013' :  flsb = '\000' ;
               break ;    /* hex 00 */

case '\014' :  flsb = '\007' ;
               break ;    /* hex 07 */
case '\015' :  flsb = '\006' ;
               break ;    /* hex 06 */
case '\016' :  flsb = '\005' ;
               break ;    /* hex 05 */
```

```
            case '\017' :  flsb = '\004' ;
                           break ;    /* hex 04 */
          }
         *code2 = fmsb|flsb ;

      }

else if ( *n <= -1  &&  *n >= -2048 )
             /*  convert  1st byte  of  binary  code  */
       {
          nn = *n+1 ; nn = (-nn);
                        /*  convert to positive range  */
          bk = nn/256 ; /*   range  is  0---- +2047     */

          switch (bk)
             {
               case '\000' : *code1 = '\274' ;
                             break ;   /* 0= hex BC */
               case '\001' : *code1 = '\275' ;
                             break ;   /* 1= hex BD */
               case '\002' : *code1 = '\276' ;
                             break ;   /* 2= hex BE */
               case '\003' : *code1 = '\277' ;
                             break ;   /* 3= hex BF */

               case '\004' : *code1 = '\270' ;
                             break ;   /* 4= hex B8 */
```

```
                    case '\005' : *code1 = '\271' ;
                                  break ;   /* 5= hex B9 */
                    case '\006' : *code1 = '\272' ;
                                  break ;   /* 6= hex BA */
                    case '\007' : *code1 = '\273' ;
                                  break ;   /* 7= hex BB */
                  }         /*  second block 1st byte cover.
*/

/*---------------- convert 2nd byte ---------------------
*/
          sbk = nn - bk*256 ;

/*    small  block  range  is  0---255
*/
          x = sbk/16 ;       /*  find first 4 MSb in code2
*/

          switch (x)         /* 256/16 = 16 ------ ( 0-15 )
*/
            {
               case '\000' : fmsb = '\100' ;
                             break ;   /* 0= hex 40 */
               case '\001' : fmsb = '\120' ;
                             break ;   /* 1= hex 50 */
               case '\002' : fmsb = '\140' ;
                             break ;   /* 2= hex 60 */
```

```
case '\003' : fmsb = '\160' ;
              break ;   /* 3= hex 70 */

case '\004' : fmsb = '\000' ;
              break ;   /* 4= hex 00 */
case '\005' : fmsb = '\020' ;
              break ;   /* 5= hex 10 */
case '\006' : fmsb = '\040' ;
              break ;   /* 6= hex 20 */
case '\007' : fmsb = '\060' ;
              break ;   /* 7= hex 30 */

case '\010' :  fmsb = '\300' ;
               break ;  /* 8= hex C0 */
case '\011' :  fmsb = '\320' ;
               break ;  /* 9= hex D0 */
case '\012' :  fmsb = '\340' ;
               break ;  /* 10=hex E0 */
case '\013' :  fmsb = '\360' ;
               break ;  /* 11=hex F0 */

case '\014' :  fmsb = '\200' ;
               break ;  /* 12=hex 80 */
case '\015' :  fmsb = '\220' ;
               break ;  /* 13=hex 90 */
case '\016' :  fmsb = '\240' ;
               break ;  /* 14=hex A0 */
```

```
      case '\017' :  fmsb = '\260' ;
                     break ;  /* 15=hex B0 */
    }
  y = sbk%16;           /*   find 4 LSB in code2   */

  switch (y)            /*  256/16 = 16---( 0-15 )*/
    {
       case '\000' : flsb = '\004' ;
                     break ;     /* 0= hex 04 */
       case '\001' : flsb = '\005' ;
                     break ;     /* 1= hex 05 */
       case '\002' : flsb = '\006' ;
                     break ;     /* 2= hex 06 */
       case '\003' : flsb = '\007' ;
                     break ;     /* 3= hex 07 */

       case '\004' : flsb = '\000' ;
                     break ;     /* 4= hex 00 */
       case '\005' : flsb = '\001' ;
                     break ;     /* 5= hex 01 */
       case '\006' : flsb = '\002' ;
                     break ;     /* 6= hex 02 */
       case '\007' : flsb = '\003' ;
                     break ;     /* 7= hex 03 */

       case '\010' :  flsb = '\014' ;
                      break ;    /* 8= hex 0C */
```

```
              case '\011' :  flsb = '\015' ;
                             break ;    /* 9= hex 0D */
              case '\012' :  flsb = '\016' ;
                             break ;    /* 10=hex 0E */
              case '\013' :  flsb = '\017' ;
                             break ;    /* 11=hex 0F */

              case '\014' :  flsb = '\010' ;
                             break ;    /* 12=hex 08 */
              case '\015' :  flsb = '\011' ;
                             break ;    /* 13=hex 09 */
              case '\016' :  flsb = '\012' ;
                             break ;    /* 14=hex 0A */
              case '\017' :  flsb = '\013' ;
                             break ;    /* 15=hex 0B */
            }

          *code2 = fmsb|flsb ;

        }

else
  { printf("!!!!!  Some kind of ERROR  in  your data file
                                                  !!!!\n\n");
    printf("!!!!!  the  integer  range  should  between
                                            +2047 to -2048\n");
    exit(1);
```

```
    }

}

/___________________________________________________________/
```

```
`

#include "stdio.h"
#define  BIN_MODE  0
#define  ASC_MODE  1
extern int _fmode;

FILE *gfopen(fn,fmode,ft)
  char fn[];
  char fmode[] ;
  int ft;
  {
     int   tmode;
     FILE  *tfd;

     tmode = _fmode;
     if ( ft == BIN_MODE )
           _fmode = 0x8000;
      else _fmode = 0 ;

     tfd = fopen(fn,fmode);
     _fmode = tmode;
     return (tfd);
   }
/*===========================================================*
/
```

APPENDIX A(6)

The three batch files using the command language of ILS-IEEE that have been used to perform autocorrelation and crosscorrelation of the various signals in this research work will be listed here. Also, the various ILS commands that have been used will be explained with brief comments to each line.

A (6.1) AUTOECG.BAT

With the file XX99, containing the digitized ECG, available in the default directory autocorrelation can be performed by keying in AUTOECG to the C:\ prompt. The command sequence is as follows:

FIL DEY300,,3	; deletes or cleans up three files starting from file 300; these files will later be used for file manipulation
FIL 99	; this will load file 99 from the default directory
FIL S300	; selects file S300 as secondary A file
OPN S3,30	; opens three consequitive record files starting with s300 with 30 data blocks preallocated to each record file
SRE 1,25,256	; stores sample-data as records in file S300 as 25 time series records for the COR program with 256 points per storage window
FIL 300	; loads file 300 which is a record file

FIL S301	; file S301, already opened, is selected as a secondary file
COR A	; autocorrelates the record file containing the electrocardiogram signal and stores the result as one record in secondary file s301
DRE S1,1	; record 1, a single record result of autocorrelation stored in record file S301 is displayed

A (6.2) AUTOMI.BAT

With the fil XX100, containing the digitized microwave interferometer signal, available in the default directory autocorrelation can be performed by keying in AUTOMI to the C:\ prompt. The ILS command sequence is as follows:

FIL DEY400,,3	; deletes or cleans up three files starting from file 400; these files will later be used for file manipulation
FIL 100	; this will load file 100 from the default directory
FIL S400	; selects file S400 as secondary A file
OPN S3,30	; opens three consequitive record files starting with s400 with 30 data blocks preallocated to each record file
SRE 1,25,256	; stores sample-data as records in file S400 as 25 time series records for the COR program with 256 points per storage window

FIL 400	; loads file 400 which is a record file
FIL S401	; file S401, already opened, is selected as a secondary file
COR A	; autocorrelates the record file containing the microwave interferometer signal and stores the result as one record in secondary file s401
DRE S1,1	; record 1, a single record result of autocorrelation stored in record file S401 is displayed

A (6.3) CROSSCOR.BAT

The digitized ECG pulse train in file XX101 and the digitized microwave data in file XX100 can be crosscorrelated by running CROSSCOR.BAT at the C:\ prompt. The sequence of commands are as follows:

FIL DEY 102,,6	; deletes or cleans up six files starting from fil 102
FIL 100	; this will load fil 100 from the default directory (primary A-file)
FIL S103	; selects fil S103 as secondary A-file
OPN SICOR3	; three files are opened starting with secondary file S103, and all given the identification "cor"

```
SRE 1,25,256        ; stores sample-data as records in file
                      S103 as 25 time-series records for the
                      COR program with 256 points per storage
                      window.
FIL 103             ; loads file s103 which is a record file

FIL B104            ; selects file 104 as primary B-file.

FIL S105            ; file 105 (already opened) is selected as
                      the secondary file

COR C1,1            ; crosscorrelation of the primary A-file
                      and primary-B file is done for the first
                      record.

COR C1,25           ; twenty-five records of primary A-file
                      and primary B-file are crosscorrelated

DRE 1,1,,,,,2       ; DRE is used to display the first record
                      of two consecutive files, the primary
                      (103) and the next (104); these contain
                      the interferometer and the ECG pulse
                      train signals respectively

PAUSE               ; the programmed is paused so that the
                      display on screen produced by DRE can be
                      printed.  After printing is over the
```

```
                    program asks the user to hit any key to
                    continue

CLEAR             ; this clears the screen

DRE S1,1          ; Record one, a single record correlation
                    of the secondary fil is displayed.

PAUSE             ; execution is temporarily halted

DRE S2,1          ; record two of the 25 record
                    crosscorrelation, of the secondary file,
                    is displayed.

PAUSE             ; the program pauses until the operator
                    asks to continue by pressing any key on
                    the keyboard

CLEAR             ; the screen cleans up and ends the
                    program.
```

Appendix (B)

DASH-16 A/D - D/A CONVERTER BOARD

Dash-16 manufactured by Metrabyte Corporation is a multifunction high speed analog/digital I/O expansion board for the IBM personal computer. The board is of multilayer construction with integral ground plane, to minimize noise and crosstalk at high frequencies. DASH-16 uses an industry standard (AD574A) 12 bit successive approximation converter with a 25 microsecond conversion time. The channel input configuration is switch-selectable on the board, providing a choice between 16 single-ended channels or 8 differential channels with 90dB common mode rejection and ±10Volts common mode range. The DASH-16 has high input impedance ranges of +1V, +2V, +5V, +10V in the unipolar mode and ±0.5V, ±1.0V, ±2.5V, ±5.0V, and ±10.0V in the bipolar range.

The A/D converter board is set-up for this experiment as follows:

1. DASH-16 requires 16 consecutive address locations in I/O space. Some I/O locations will be occupied by the internal I/O and other peripheral cards of the computer. To provide flexibility in avoiding conflict with these devices, DASH-16's I/O address can be set by a BASE ADDRESS D.I.P. switch on a 16 bit address boundary anywhere in the IBM-A/T personal computer decoded I/O space. The selected address is Hex 300 (which 768 decimal).

2. Using the channel configuration switch (CHAN CNFG), 16 single-ended or 8 differential channels can be selected. As per our signal requirement, 8 bipolar channels is the appropriate configuration.

3. There is a slide switch which controls the input signal range. In the UNI (unipolar) position, input signal voltages can only be positive; in the BIP (bipolar) position, both positive and negative voltages are acceptable. As per our requirement the BIP position is selected.

4. There is yet another slide switch which selects the DMA operating level (1 or 3). This switch is set to level 3.

5. Using the GAIN selection D.I.P. switch the gain as well as magnitude range of the input voltage is selected. Only one element of this D.I.P. switch should be in the ON position. This switch is set for GAIN = 2, BIPolar $\pm$2.5V.

APPENDIX (C)

SUBJECT'S CONSENT STATEMENT

Name of Project Director or Principal Investigator :
Dr. Peter E. Engler

Title of Project:
Microwave Interferometer As A Cardiopulmonary Monitor

I acknowledge that on ____________, I was informed by Dr. Engler of the New Jersey Institute of Technology of a project concerning or having to do with the following :
USE A MICROWAVE INTERFEROMETER TO RECORD THE VIBRATION OF MY CHEST WALL.

I was told with respect to my participation in said project that :
(1) The following possible risk are involved:
ILLUMINATION OF MY CHEST WALL WITH ELECTROMAGNETIC ENERGY AT A FREQUENCY OF 10 GHz, AND A POWER DENSITY THAT DOES NOT EXCEED 0.01mW/cm, PRECAUTION OF THE EYES WILL BE TAKEN.

(2) The following procedures are involved:
LYING QUITELY ON A LAB BENCH, I MAY BE ASKED TO HOLD MY BREATH FOR A FEW SECOND, AND I MAY BE ASKED TO DO SOME MILD CALISTHENICS TO ELEVATE HEART RATE PRIOR TO TEST.

(3 The following benefits are expected by my participation:
DEVELOPMENT OF A UNIQUE CLINICAL INSTRUMENT AND DIAGNOSIS OF CARDIOVASCULAR PROBLEMS/ABNORMALITIES.

I am fully aware of the nature and extend of my participation in said project and possible risk involved or arising thereform. I hereby agree, with full knowledge and awareness of all of the foregoing, to participate in said project. I further acknowledge that I have received a complete copy of this CONSENT STATEMENT.

I also understand that I may withdraw my participation in the said project at any time.

Date:__________

____
Signature of Subject or Responsible Agent

Place:____________________________________
(City & State) (Printed Name of Subject or Agent)

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(Residence Address of Subject or Agent)

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