An Algorithm Development Support System for the Analysis of Cardiac Arrhythmia.

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Being a working mother and part time graduate student has not been easy. I wish to dedicate this report to my parents and to my son, who was my inspiration through all of this.

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Chapter I

INTRODUCTION

The human body is a complex machine, which produces numerous signals. These signals can be used to analyze many conditions and functions. Among these are the "sounds" or electrical signals produced by the beating heart. These "sounds" can be heard by simply placing the ear against the chest or through more sophisticated methods such as electrocardiography, which permits the recording, even at the surface of the body, of these signals and their display on a chart as complex curved lines. The reading or interpretation of these signals can provide valuable information as to the well-being of the heart as well as aid in diagnosing various arrhythmias.

The objective of this project is to develop a user-friendly PC software system that will aid the detection of cardiac arrhythmia in the analysis of ambulatory ECG tapes. The system displays the signals as recorded and gives the user the choice of applying various transformations to these signals, transformations that would help in characterizing certain abnormalities.

Chapter II

THE ELECTROCARDIOGRAM

2.1 - INTRODUCTION.

The design considerations of an ECG recording analysis system are very much tied to the type of signals to be analyzed. Before engaging in a discussion on the types of systems that exist and what work is being done in this project, it is useful to explain what these systems are examining. This chapter will give a brief description of the ECG signals and the relationship between the characteristics of these signals and the anatomy of the heart. The chapter will end with an overview of the abnormalities that the system being developed in this project is designed to detect and will illustrate the recordings.

2.2 - ANATOMY OF THE HEART.

Before explaining the functioning of an ECG and the results obtained, it is necessary to give a brief description of the heart structure.

The heart is a four-chambered muscle. The four chambers are arranged in two functionally similar pairs. Each pair consists of a thin-walled atrium and a thicker walled ventricle. The atrium receives blood from the veins and pushes it into the ventricles, which in turn pump the blood out of the heart and into the body. Each pair is more commonly known as the right and left heart, which are independent from each other. There are specialized heart tissues, known as the nodal tissues, which instigate and regulate the heart beat. They consist of the sinoatrial (S-A) node and the atrioventricular (A-V) node which branches out into the Bundle of His. The S-A node is located in the upper part of the right atrium. It initiates the heart beat and regulates its contraction. For this reason it is also known as the "pacemaker" of the heart. This electrical impulse is propagated throughout the atria, which causes them to contract and push blood into the ventricles. The A-V node is located at the bottom of the two atria. It is stimulated by the electrical impulses it receives from the atria and passes these impulses to the ventricles by way of a nerve network called the Bundle of His. This bundle

of nerves leads to the Purkinje system through which the electrical waves are propagated to the ventricles, causing them to contract and pump the blood out of the heart. See figure 2.1.

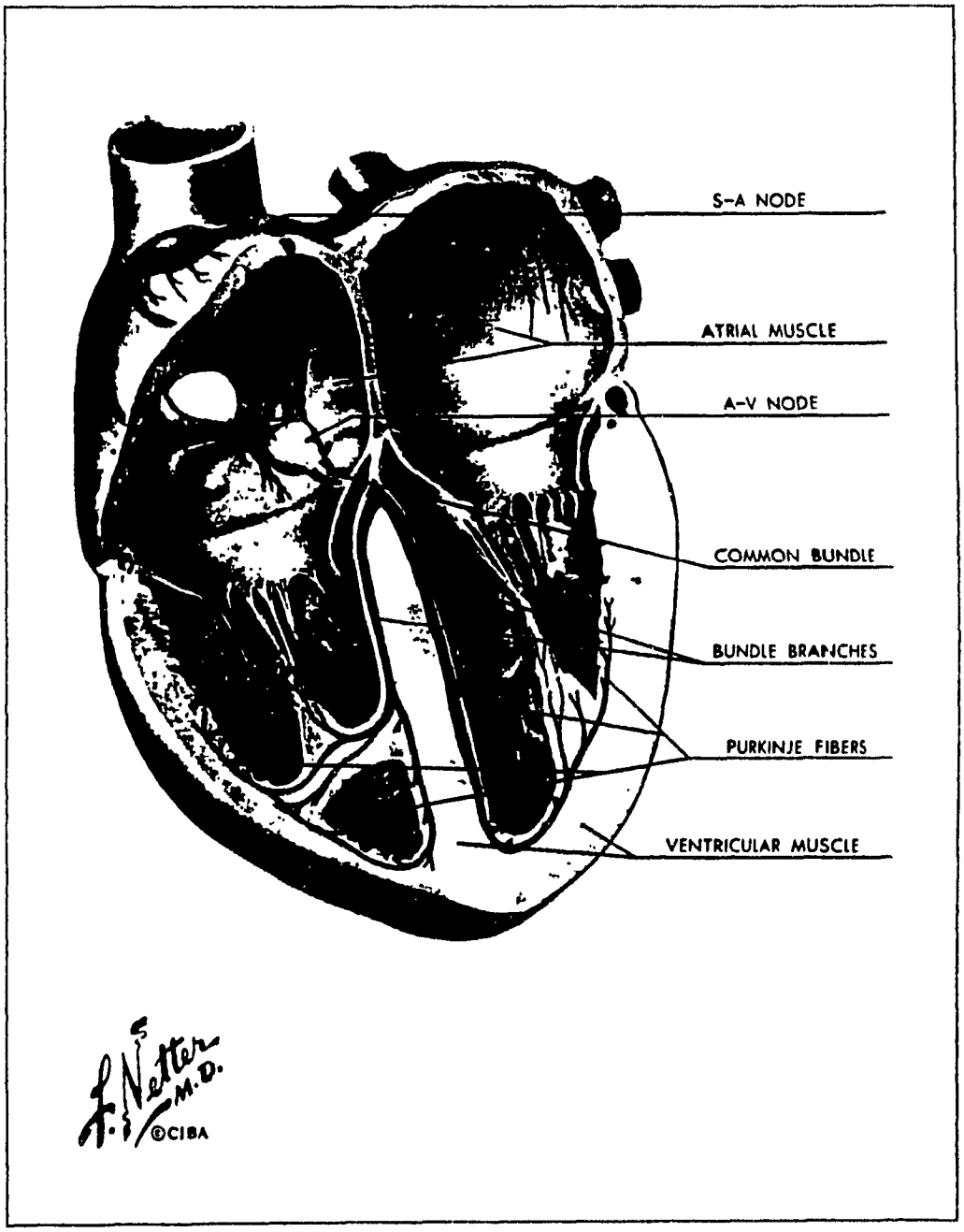


Fig. 2.1 - Anatomy of the heart. [25]

2.3 - THE ELECTROCARDIOGRAM.

What is an electrocardiogram?

An electrocardiogram (ECG) is a graph of voltage variations plotted against time. The variations result from the depolarization and the repolarization of the cardiac muscle as it contracts and relaxes. This produces electric fields that reach the surface of the body where electrodes are placed to capture them [25]. These electrodes are taped to the skin in various locations including the back, the limbs and the heart region.

Relation of the ECG to the heart.

The normal ECG is made up of a series of five oscillations arbitrarily referred to as the P, Q, R, S and T waves, illustrated in figure 2.2. Each wave corresponds to the polarization and depolarization of the heart muscle.

The P wave is the result of the atrial depolarization or contraction initiated by the S-A node. The PR interval is a measure of the time interval from the beginning of atrial contraction to the beginning of ventricular contraction. It normally is between 0.12 and 0.20 seconds. The QRS complex corresponds to the contraction of both ventricles. The QRS duration is usually between 0.06 and 0.10 seconds. The T wave

is the result of the relaxation or polarization of the ventricular muscle. The Q-T interval varies with the heart rate and is usually less than half the preceding heart beat. Each heart cycle is made of a P, QRS and T wave and referred to as the R-R interval. The heart rate is determined by counting the number of R-R intervals or heart beats per minute. See a summary of the ECG intervals in figure 2.3.

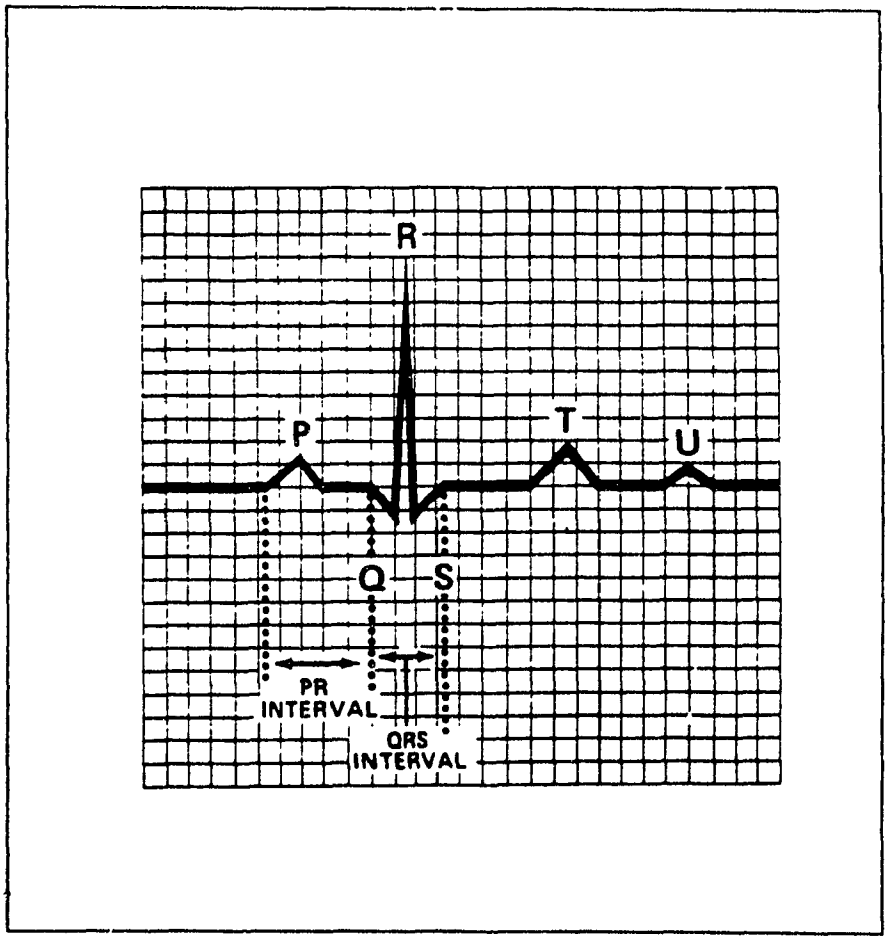


Fig. 2.2 - The electrocardiogram. [23]

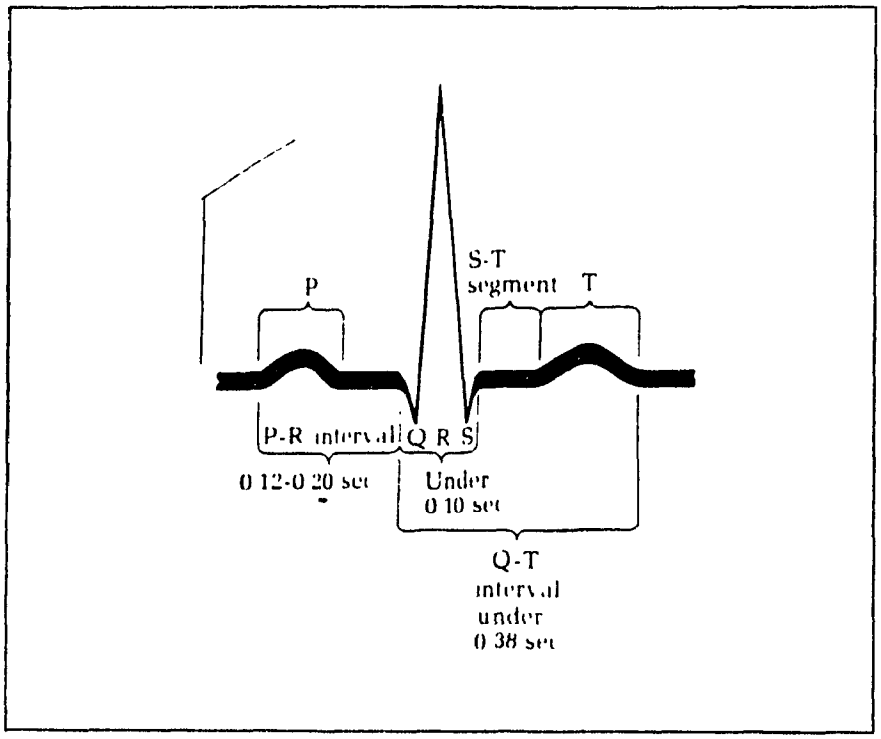


Fig. 2.3 - The ECG intervals. [8]

The relation of the anatomy of the heart to the ECG rhythm can be seen in figure 2.4. Note that the center line is at the branches of the Bundle Of His. Malfunctions above this line will affect the P wave and the PR interval, whereas malfunctions below this line will be seen in the QRS complex.

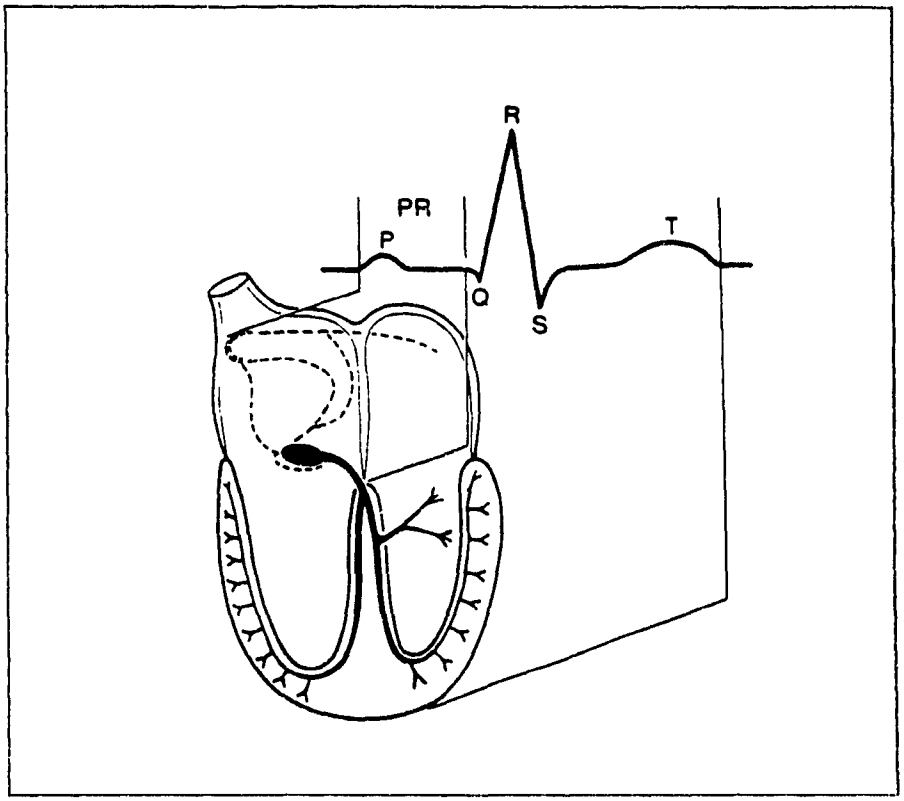


Fig. 2.4 - Relation of the anatomy of the heart to the ECG rhythm. [23]

2.4 - CARDIAC ARRHYTHMIA.

The terms *dysrhythmia*, *arrhythmia* and *ectopic beat* are used interchangeably in most medical publications. However dysrhythmia refers to a disturbance in rhythm whereas arrhythmia is characterized by the absence of rhythm [23]. On the other hand, a single spurious impulse appearing at odd times and causing an aonormal beat is called an ectopic beat [16]. In this report, arrhythmia and ectopic beat will be used interchangeably to refer to abnormal cardiac activity.

Abnormal cardiac rhythm can be caused by abnormal rhythmicity of the pacemaker itself, shift of the pacemaker from the S-A node to other parts of the heart, blocks at different points in the transmission of the impulse through the heart, abnormal pathways of impulse transmission throughout the heart and finally spontaneous generation of abnormal impulses in almost any part of the heart [16]. There are hundreds of types of arrhythmia as classified by the medical profession. It is almost impossible to program an automated system for so many variations.

The idea behind ambulatory ECG is to observe partially ill or apparently healthy individuals in order to detect arrhythmias that are indicative of more serious cardiac problems. This criterion reduces the number of arrhythmias that will be considered in the implementation of the automated system

described in this report. Those arrhythmia disorders that are considered in this system will be briefly described in the following sections.

When analyzing an ECG for possible arrhythmia, the key is in evaluating the inter-relation of the P wave, the PR interval, and the QRS complex, with its width and configuration [23].

Premature Contractions.

Often, a small area of the heart becomes much more excited than normal and causes an occasional abnormal beat to be generated between normal impulses. This initiates a premature contraction [16]. The beats can occur as isolated complexes or in succession as pairs. They are two types of premature contractions: the *Premature Ventricular Contraction* (PVC) and the *Premature Atrial Contraction* (PAC).

The *Premature Ventricular Contraction* is an early contraction of either ventricle. This results in wide and often bizarrely shaped QRS complexes. The P wave is often nonexistent. The T wave following the PVC is often large and in the opposite direction of the QRS complex. Figures 2.5a, b, c show three examples of PVCs.

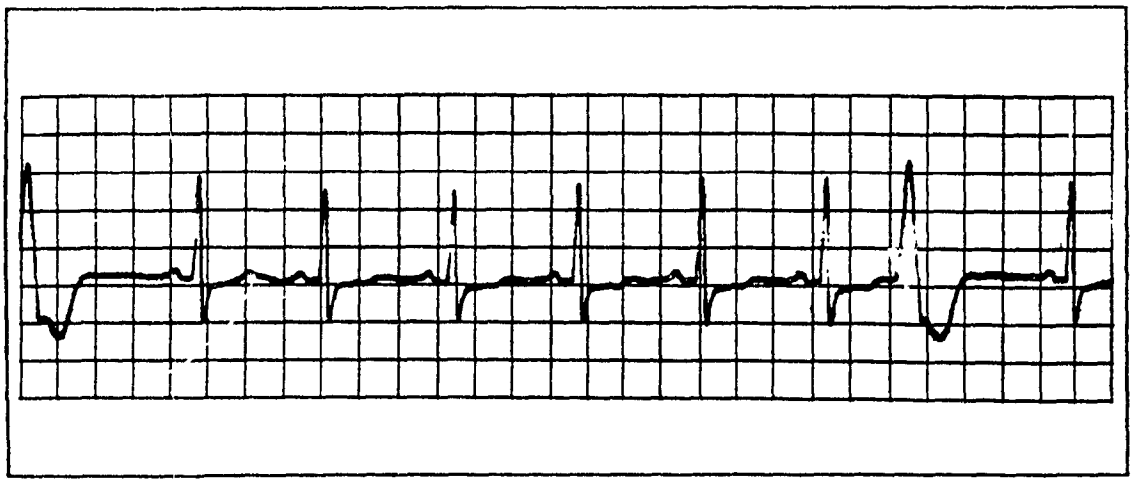


Fig. 2.5a - Premature Ventricular Complexes. [23]

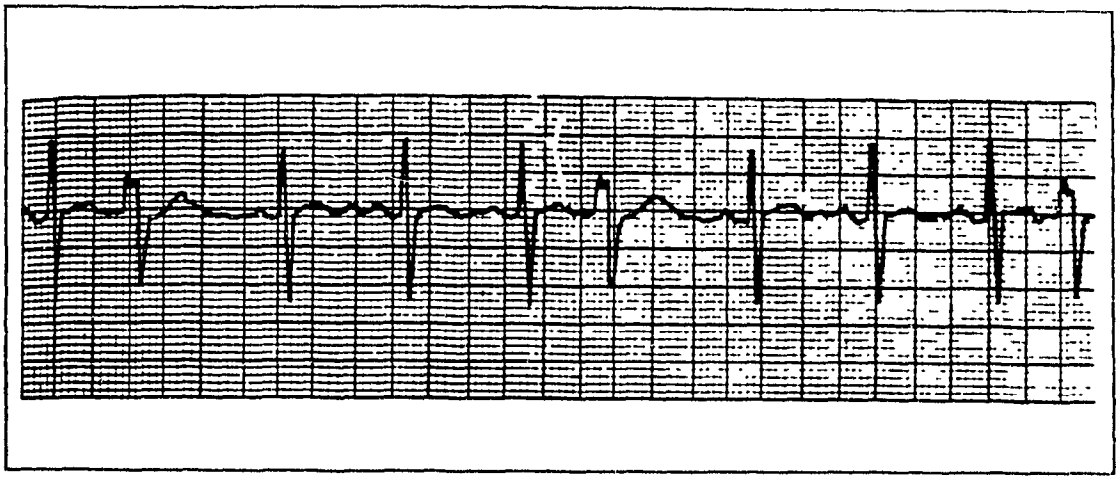


Fig. 2.5b - Pairs of Premature Ventricular Complexes. [23]

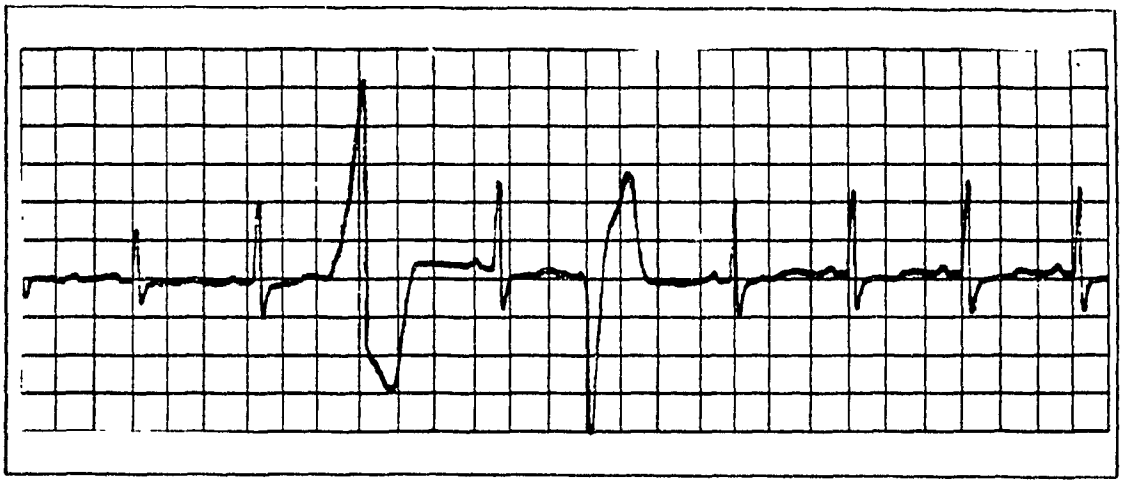


Fig. 2.5c - Multiformed Premature Ventricular Complexes. [23]

Ventricular Bigeminy is a rhythm where every other beat is a PVC. Similarly *Ventricular Trigeminy* is used to describe two normal beats and one PVC, or sometimes one normal beat and two PVCs. Two normal beats and one PVC is the preferred use of Ventricular Trigeminy.

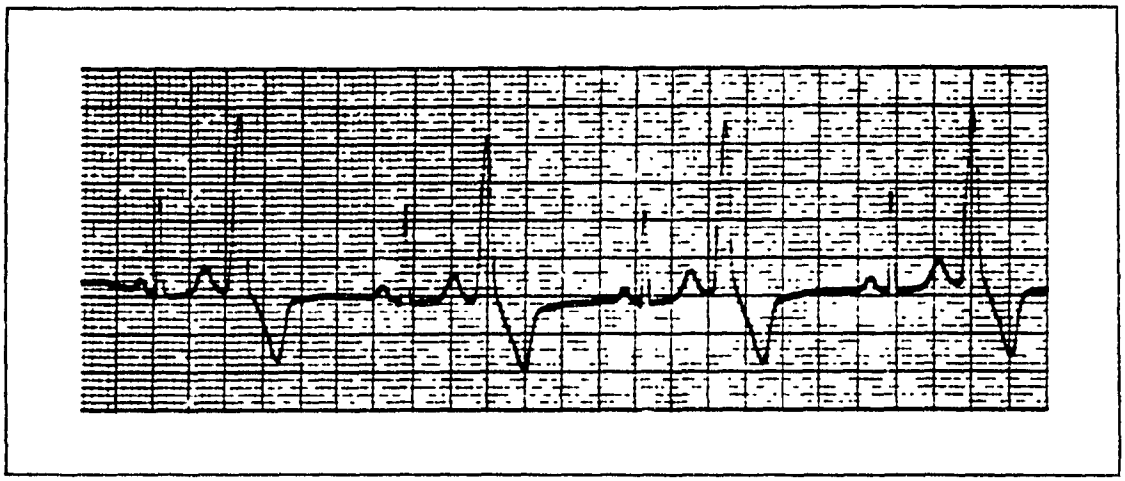


Fig. 2.6 - Ventricular Bigeminy. [23]

The *Premature Atrial Contraction* (PAC) is a premature contraction of either atrium. They often occur without any apparent causes. The commonly recognized causes are the so called "stimulants" such as caffeine, tobacco, alcohol, and certain drugs, which result in an irregular heart rhythm. The QRS complex is usually normal, however the P wave is premature and ectopic. The interval between the premature P wave and the next sinus P wave is equal to or a bit longer than the usual P-P interval. This is why the P wave preceding and following the PAC is often less than twice the normal P-P interval. This is known as a noncompensatory pause [23]. See figure 2.7a.

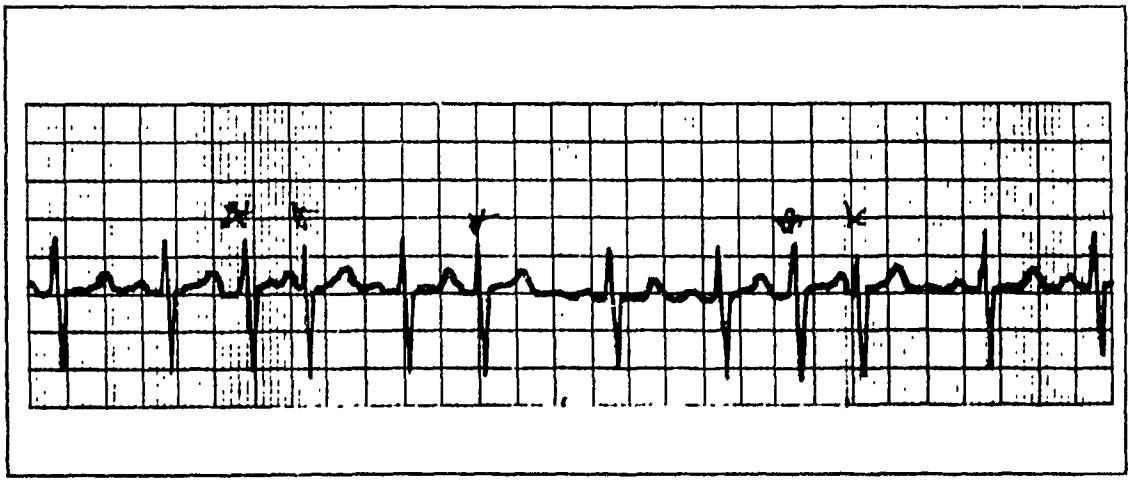


Fig. 2.7a - Premature Atrial Complexes. [23]

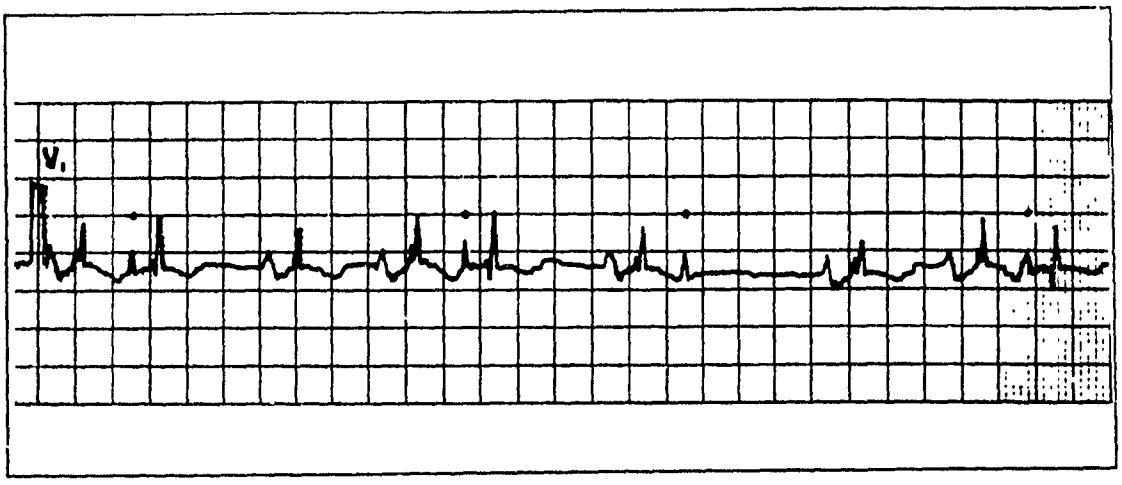


Fig. 2.7b - Multiple Premature Atrial Complexes. [23]

Sinus Arrhythmia.

Sinus Arrhythmia is a variation in the heart beat during breathing due to an irregular rate in the pacemaker. The heart rate increases during inspiration and decreases during expiration. In the ECG, it is reflected through the following signs: there is one P wave per QRS complex, the PR interval is constant and the RR interval varies from heart beat to heart beat.

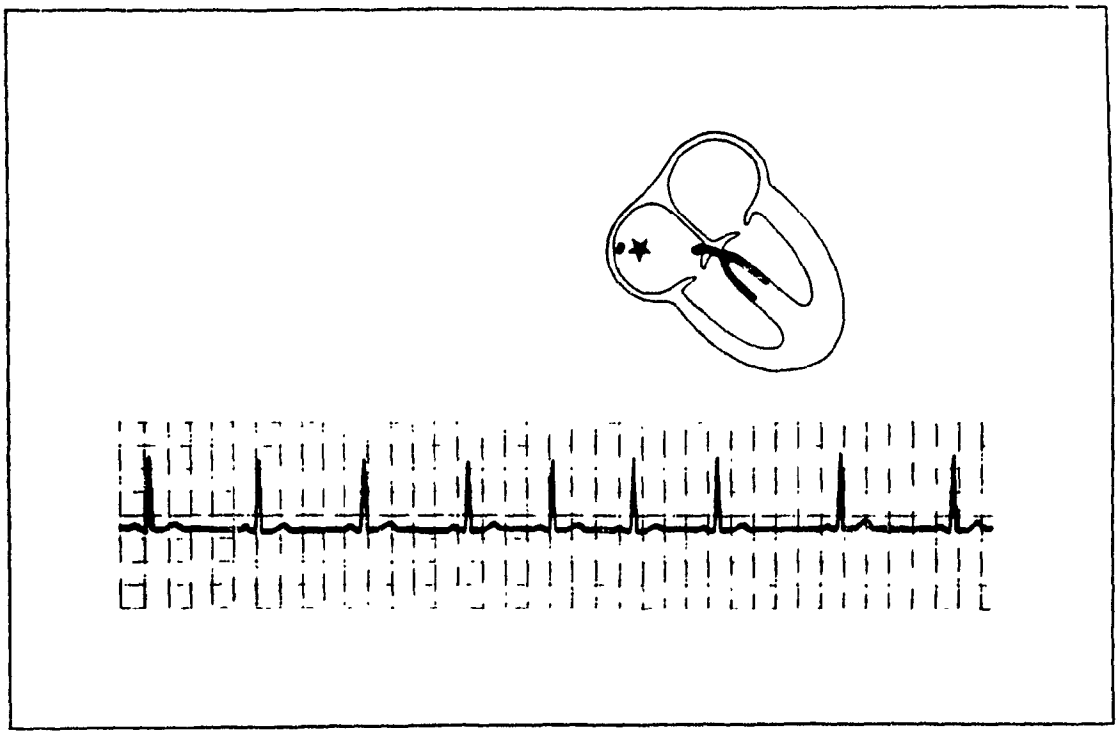


Fig. 2.8 - Sinus Arrhythmia. [18]

Tachycardia, Fibrillation and Atrial Flutter.

Tachycardia refers to the excessive rapidity in the action of the heart. It is usually used in conjunction with heart rates above 100 per minute. There are different types of tachycardia.

Sinus Tachycardia represents an increase in the discharge of the sinus node. It may be caused by such factors as exercise, pain, emotion, fever, anxiety, and is a result in the demand for a higher cardiac output. The QRS complex is preceded by an upright P wave (fig. 2.9).

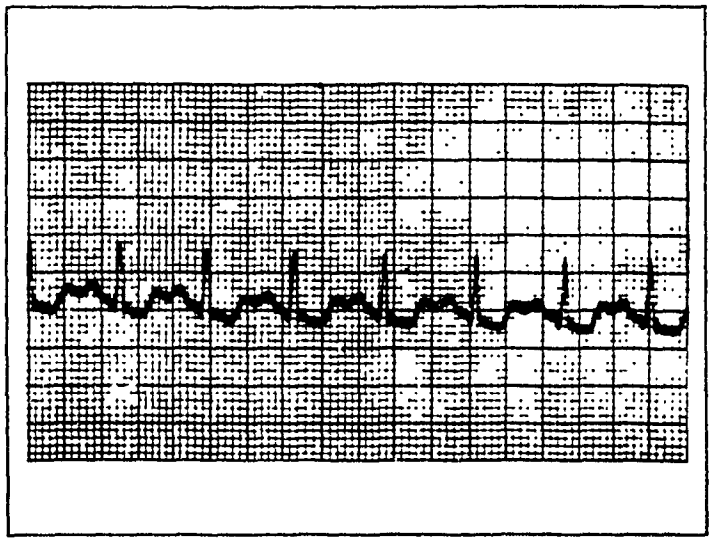


Fig. 2.9 - Sinus Tachycardia. [23]

Atrial Tachycardia (AT) is due to a pacemaker in the atrium which gives rise to rapid regular impulses at a rate above 100 beats per minute. The P and T waves sometimes fall on each other. The condition is characterized by a sudden beginning and ending. Sometimes a QRS complex fails to appear. This is known as an *Atrial Tachycardia with Block* (Fig. 2.11). This means that there is a block at the A-V node.

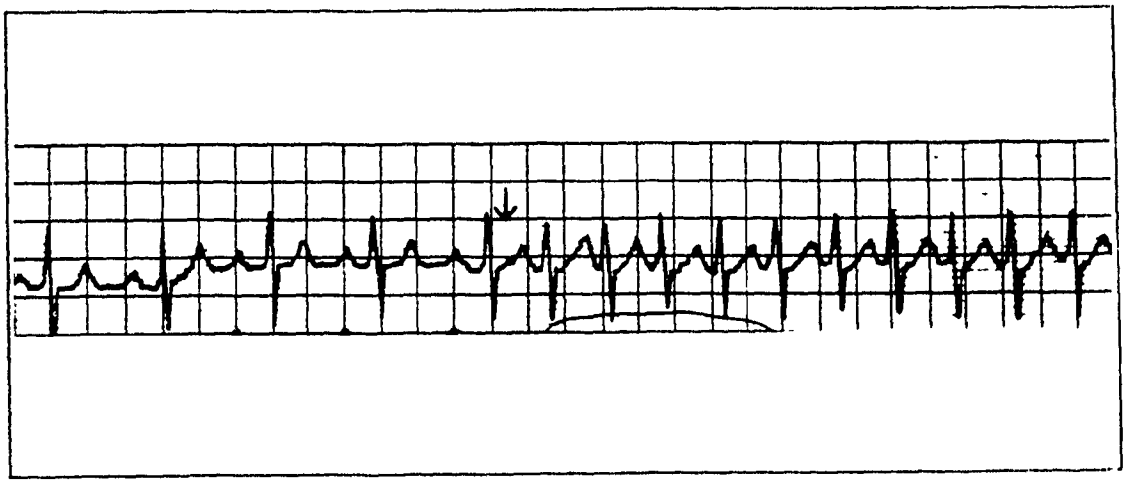


Fig. 2.10 - Atrial Tachycardia. [23]

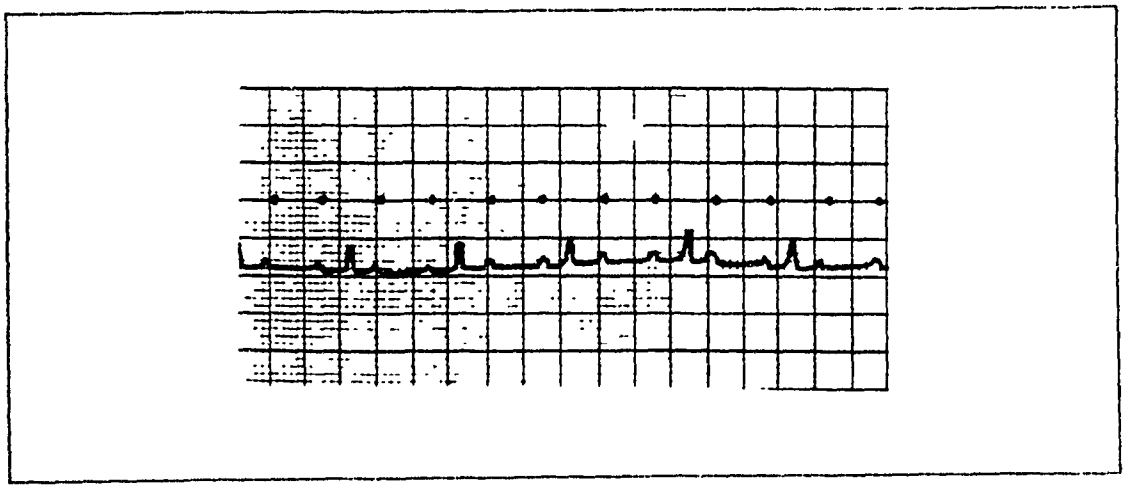


Fig. 2.11 - Atrial Tachycardia with block. [23]

Ventricular Tachycardia (VT) is a serious cardiac condition. It entails an abnormally high ventricular rhythm with aberrant ventricular excitation, seen in the form of the QRS complexes which are very wide. The interval and the shape vary slightly from one beat to the next. Often the P wave is not recognizable. In other terms it is a series of successive Premature Ventricular Contractions.

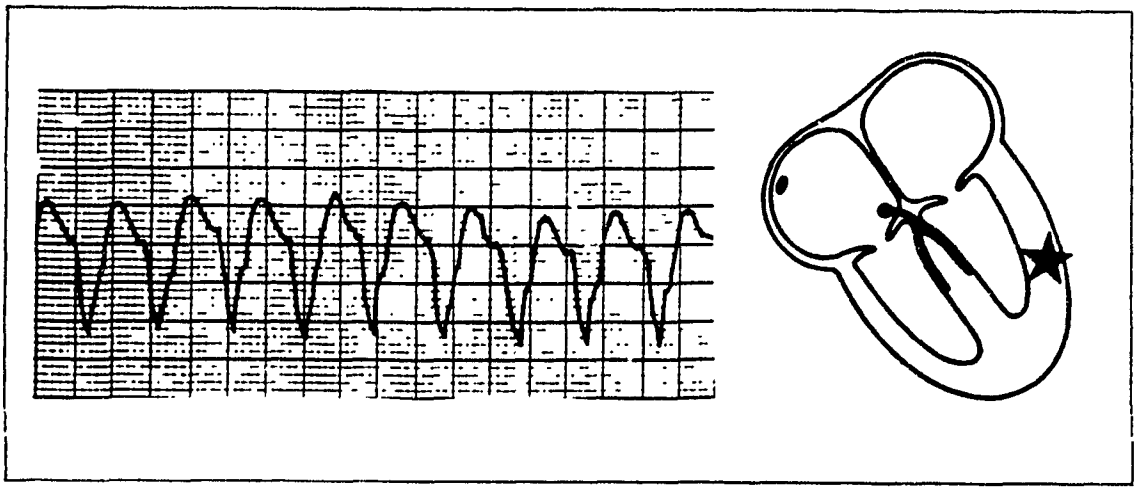
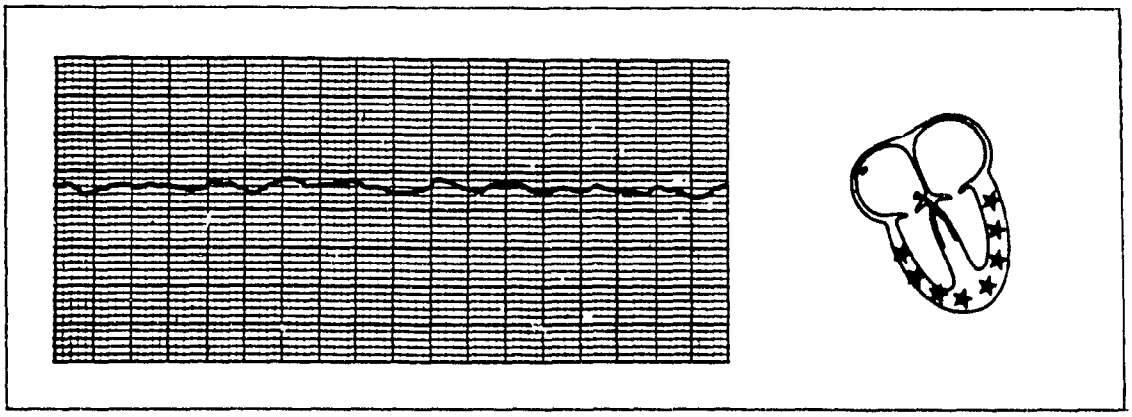


Fig. 2.12 - Ventricular Tachycardia. [18,23]

Ventricular Fibrillation is the result of erratic depolarization of the ventricles. It produces distorted sine waves that are irregular in amplitude and duration. This is a most dangerous situation as there is no effective pumping of the heart, often resulting in sudden death. It is easy to detect since by the time it would take to determine that the erratic waves produced are not due to a malfunctioning in the equipment, the patient will usually have fainted.



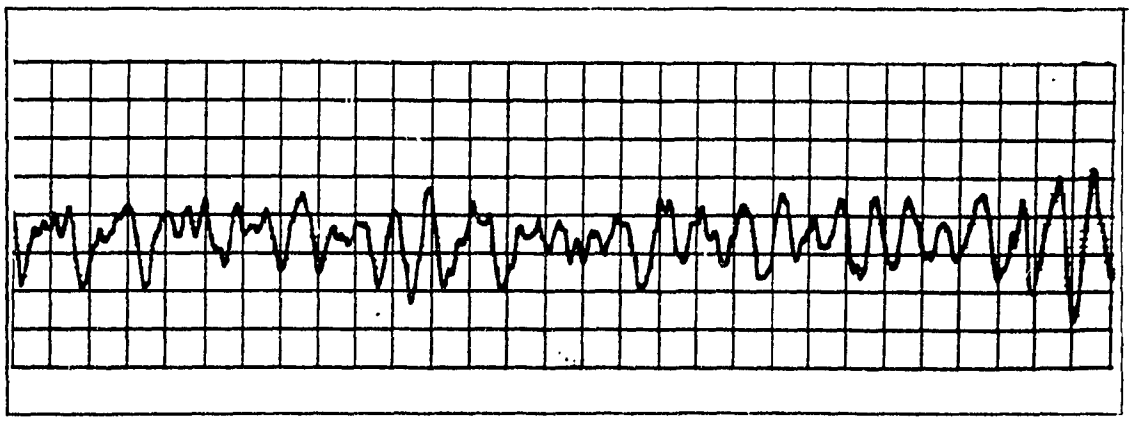


Fig. 2.13 Two examples of ventricular fibrillation. [18,23]

Atrial Fibrillation (AF) is due to islands of abnormal tissue, causing the atrial depolarization wave to wind its way in and out of these islands of tissue. As a result, there is no contraction of the atria as a whole, therefore no P wave and irregular QRS complexes. The R-R intervals are all different.

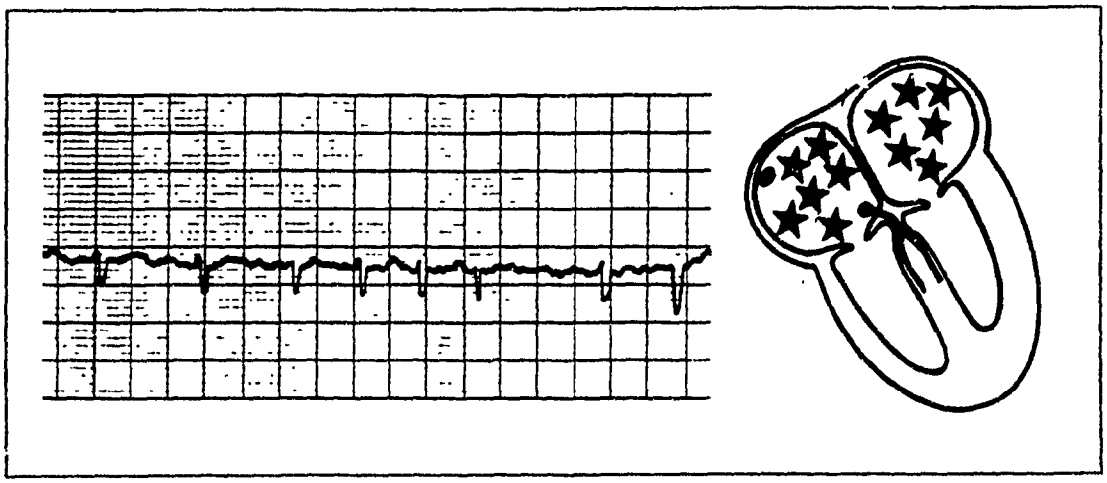


Fig. 2.14 - Atrial Fibrillation. [18,23]

Following is a tabular summary of how the abnormalities of the cardiac rhythm can be systematically analyzed.

P-wave	P/QRS	Regularity of QRS	Shape of QRS	Frequency of QRS	Condition
non existent			abnormal (wide)		*PVC*
			Every other beat is a PVC		*Ventricular Bigeminy*
			Every third beat is a PVC		*Ventricular Trigeminy*
ectopic premature			normal		*PAC*
			normal	rapid	*Sinus Arrhythmia*
				Faster than Normal	*Sinus Tachycardia*
P & T fall on each other		regular	normal	rapid	*Atrial Tachycardia*
	QRS fails to appear	regular	abnormal	rapid	*AT with Block*
absent non-recognizable		slightly irregular	abnormal (very wide)	rapid	*Ventricular Tachycardia*
	no QRS wave				*Ventricular Fibrillation*
absent		very irregular	normal	any	*Atrial Fibrillation*

Fig. 2.15 - Systematic analysis of the abnormalities of the cardiac rhythm (summary).

From these examples, we can see that an arrhythmia classification system requires the following informations: beat detection, a running average of beat intervals, beat shape, and "P-Wave" location. The beat location will delimit the QRS complexes and is the first requirement of an analysis system. Once the intervals have been marked, we can proceed to the analysis of these beats such as the calculation of beat intervals and averages. By comparing the beat interval of the current beat with that of the running average, the user can decide whether the current beat is normal, premature or irregular. A running average can however be misleading if some of the beats are very irregular. This will corrupt the average, resulting in a unrealistic basis of comparison. Once a beat has been located, the user can also analyze its shape to determine for example if it is too wide, a possible sign of ventricular fibrillation. The detection of the P-Wave is also used in the classification of abnormalities of the cardiac rhythm. For example if it is absent it may indicate atrial fibrillation. Chapter 3 will explain the design considerations of the system developed and will clarify how some of these functions can be implemented.

Chapter III

DESIGN

3.1 - INTRODUCTION

The purpose of this system is to be a tool that will assist in the process of detecting and classifying heart beats. This task under ideal conditions is not a complex one, since QRS waves are clearly defined in the time domain, and are easy to detect due to their specific characteristics from other heart activities. However many factors make this process a non trivial one in ambulatory ECG recordings. Due to the lack of control of the conditions under which the signals are recorded, noise and other disturbances make the detection of QRS waveforms difficult. The system developed in this project will attempt to facilitate the task of analyzing the ECG recordings by providing as many tools as possible. This system is not meant to be a commercial product, but rather a prototype that could be refined at a later date.

Analysis of the ECG begins with the "detection" and "delineation" of the QRS complexes. The accuracy of these algorithms will determine the reliability and versatility of the analysis phase. Detection is the process of identifying a specific point in the waveform. This is usually done by scanning the incoming signals and detecting a point that is on a rapidly increasing or decreasing slope. Delineation is the process of identifying the beginning and end of each wave.

Once this is done, the "analysis" phase can begin. This is where the waveform can be identified as to what type of waveform it is, based on shape, timing and rhythm diagnosis. [35] The discussion in this section will also be broken into two parts: beat detection and waveform identification.

3.2 - GENERAL DESIGN CONSIDERATIONS.

As we begin the design of the system, numerous difficulties arise, i.e. points to take into consideration while designing the system. Based on the literature on the subject, here are a few of the main concerns.

Different ECG interpretations.

There are two types of ECG systems. Those that record heart beats for a few seconds and those that record much longer samples such as 24 hours of ECGs. The first one is sufficient for diagnosing cardiac diseases. These ECGs are usually recorded on paper in a clinic or hospital environment. They are used for the detailed examination of the heart beat to detect diseases. The longer records are used in intensive care units where patients must be monitored for longer periods of time as well as for ambulatory ECG recording analysis.

In the analysis of 24-hour ECG recordings from ambulant subjects, the recordings are carried out on subjects that are free to go about their everyday activities. This allows for samples to be taken under a variety of conditions. This method was found to be more effective for the detection of arrhythmia, since it is important to scan consecutive beats, to look for variations in beat shapes and the classification

of irregular beat shapes [6,26]. The most important disadvantage of this method is the volume of data involved in the analysis process.

Limitations of the computer in the ECG analysis.

As attempts are being made to substitute computers to humans for observation of cardiac rhythms, the difficulties involved are surfacing. The complexity of arrhythmias has made it difficult to create a truly effective system. Even though, according to most textbooks, the characteristics of arrhythmias are clearly different than those of healthy heartbeats, real life situations have shown different. Unfortunately, the numerous arrhythmias do not always follow the rules found in textbooks. This has fed into the difficulties encountered in developing reliable systems [13].

Unlike the human, the computer needs precise and detailed guidelines to accurately detect and classify the various ECG waves. This is a field which will undoubtedly be evolving for many years yet.

The effect of artifact.

Artifact is any product of the ECG that is not caused by the currents generated during the cardiac cycle. Artifact, or noise, is often confused with real signals in the ECG by

automated arrhythmia detection systems. Existing systems are acknowledged as being imperfect due to the difficulty in detecting noise and complex arrhythmias. The two difficulties are linked together since the inability to properly detect noise and separate it from the true heart signal inhibits the reliable detection of P, QRS and T waveforms. Noise can be the result of body movement, poor skin contact of leads, electrical or mechanical artifact in the recording device, loose or broken wire connections or even mechanical "noise' in the equipment when playing back the signal.

3.3 - DETECTION OF A BEAT.

The first step is to detect a heart beat. Many methods have been suggested and implemented to date. The most promising one has been the detection of the QRS complex: it is the most distinctive feature of the ECG signal, due to its characteristic shape, its rapid change in slopes and high amplitude. Some have used combinations of these criteria to detect QRS complexes [13]. However this slows down the processing speed. When processing ambulatory ECG recordings, speed is important due to the size of the data being analyzed.

The QRS peak has many distinctive characteristics. The QRS can be detected by its characteristic shape through pattern recognition techniques. This is however a very time consuming method.

Another method used to detect QRS waveform is the calculation of the amplitude of the QRS [11]. This is a simple and fast method but dependent on the location of leads. This method has been shown to be unreliable when not used under ideal and controlled conditions.

Another method has been to rely on the slope of the waveform. The slope of a line can be positive, meaning that it is an up slope or negative if it is a down slope. When calculating the slope of a QRS waveform, the maximum positive slope is at the rise of the QRS waveform and the maximum

negative slope is at the fall of the QRS waveform. The negative slope seems to be of larger magnitude than any other slope. With this point of largest magnitude as reference, one complete heart cycle can be isolated.

Caceres [5] explains that to recognize a beat a stable reference point must be identified in each heartbeat. The rate of greatest negative rate of change can be best used in the logic of recognition as it is present in any subject. This point of reference always occurs during the QRS. The most negative derivative point is always at the peak of the R wave or before the peak of the S wave. Figure 3.1 shows the relation between the ECG and its first derivative. To detect the QRS complexes, the first derivative or an approximation of this can be used. A valid approximation of the first derivative is determining differences between points. This is the method used in this system.

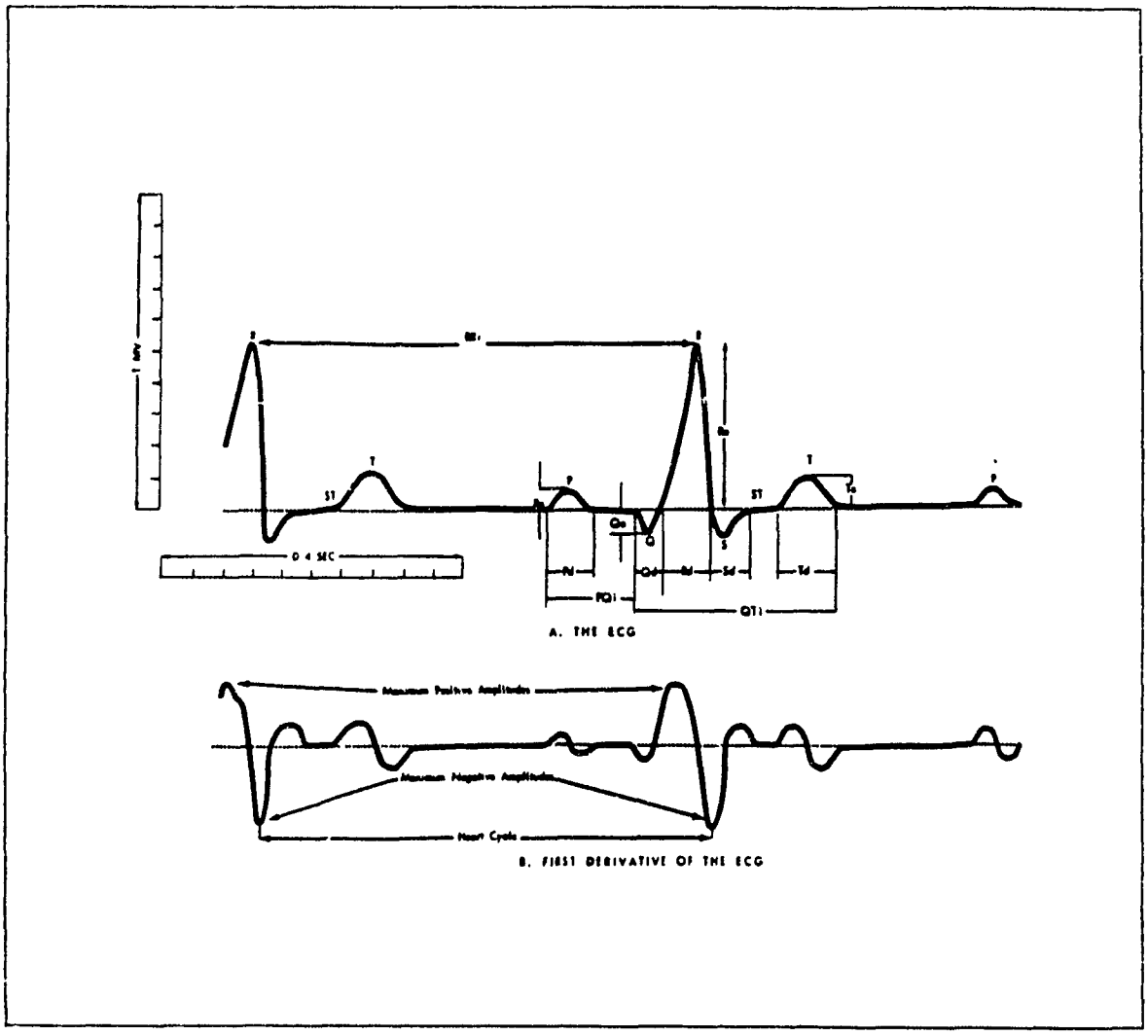


Fig. 3.1 - The ECG and the first derivative of the ECG. [5]

To calculate the first difference or slope of the ECG we simply subtract the X_i point from the X_{i+1} point. However this method does not take into consideration noise. In an attempt to minimize the effect of noise on the ECG signal, the QRS is detected by searching for a negative slope every 20 milliseconds. Also instead of using a point to point first difference, a typical approach is the two point slope measurement [36].

The difference between the point to point and the two point slope calculation is that the two point slope uses the current point X_i and the X_{i-2}.

$$S_i = X_i - X_{i-2}$$

The first difference of the signal further smoothed with a two point average results in the following calculation:

$$S_i' = \frac{X_i + X_{i-1}}{2} - \frac{X_{i-1} + X_{i-2}}{2}$$

$$= \frac{X_i - X_{i-2}}{2}$$

where X_i : value of sample i

S_i : two point slope at sample i

S_i': first difference at sample i of the signal smoothed with a two point average.

This is a simple calculation which results in reducing the effects of artifact on the ECG wave.

3.4 - CLASSIFICATION OF A WAVEFORM.

Once the detection and delineation of the QRS complexes is done, we can proceed to the analysis portion. This involves the classification of the waveforms found. Many methods have been used or described for different anomalies. Such methods as power spectrum of the ECG, sequential decision trees and Markhov chain to name a few have been used, some with more success than others. Others yet [17] have applied multivariate statistical techniques to the RR interval analysis using statistical indices and predetermined coefficients to detect certain arrhythmias. Following is a discussion of some methods, their benefits and weaknesess.

P-Wave Detection.

P-Wave detection is a difficult task due to its small magnitude in comparison with the larger QRS waveform and, of course, artifact. The detection of the P-Wave is important in the interpretation of many atrial arrhythmias. Remember that the PR interval is the measure of the time interval from the beginning of atrial contraction and the beginning of ventricular contraction.

One method used to detect P-waves is by plotting the trends of the amplitude of the P-wave [2]. The trending of a wave consists of choosing three points with fixed offsets from the fiducial point of the QRS complex. A template is then built using an "incremental averaging technique" which involves the comparison of voltage samples. Trends are then

plotted and classified based on certain criteria.

Instead of specifically attempting to isolate the P-wave a different approach has been suggested. As described by Yi-Sheng [38] and others in the literature, one method has been to cancel the QRS-T complex as the remainder ECG will carry the P-Wave information. This is accomplished via a complex filtering process known as the impulse correlated adaptive filtering technique. The largest drawback of this method is that by "erasing" the QRS-T waveform, any P-Wave overlapping the Q-Wave would be missed.

Power Spectrum analysis.

The power spectrum of the ECG is used [20] to detect ventricular tachycardia when no normal or supraventricular beats are detected for 5 seconds. The diagnosis also looks for more than 3 ventricular ectopic beats in sequence with an average frequency higher than a designated frequency. This is one way of detecting ventricular fibrillation. Clayton [3] also used the change in frequency spectrum to detect ventricular fibrillation. As can be seen in figure 3.2, during ventricular fibrillation, the signal is concentrated in a relatively narrow band usually between 4 and 7 Hz. The example of Ventricular fibrillation in figure 3.2a shows the VF band centered on 6 Hz.

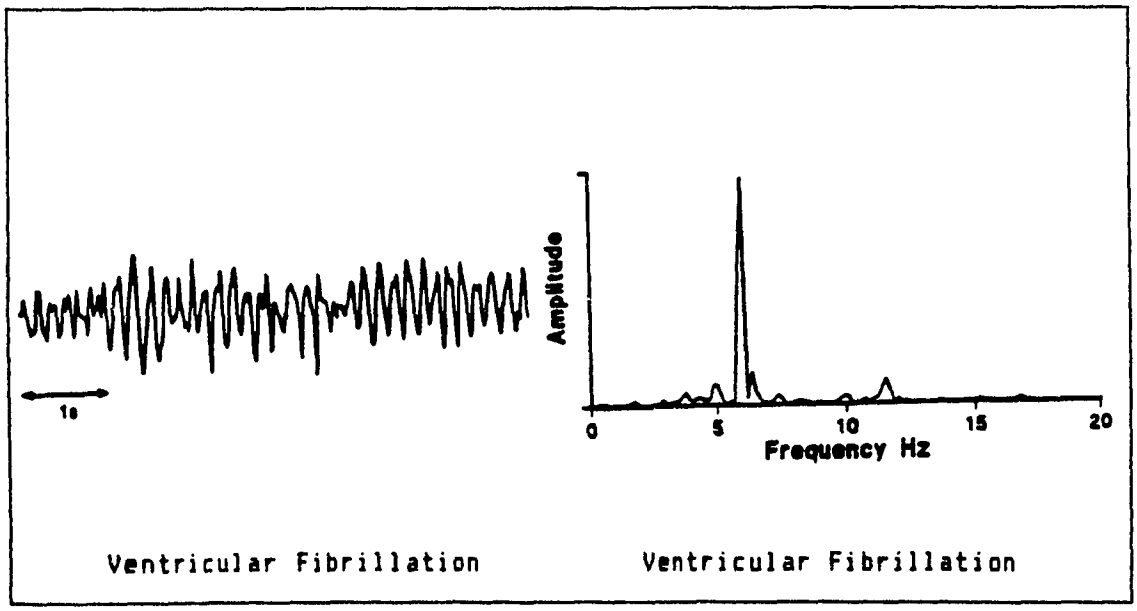


Fig. 3.2a - ECG rhythms in the time domain and power spectra of ventricular fibrillation. [7]

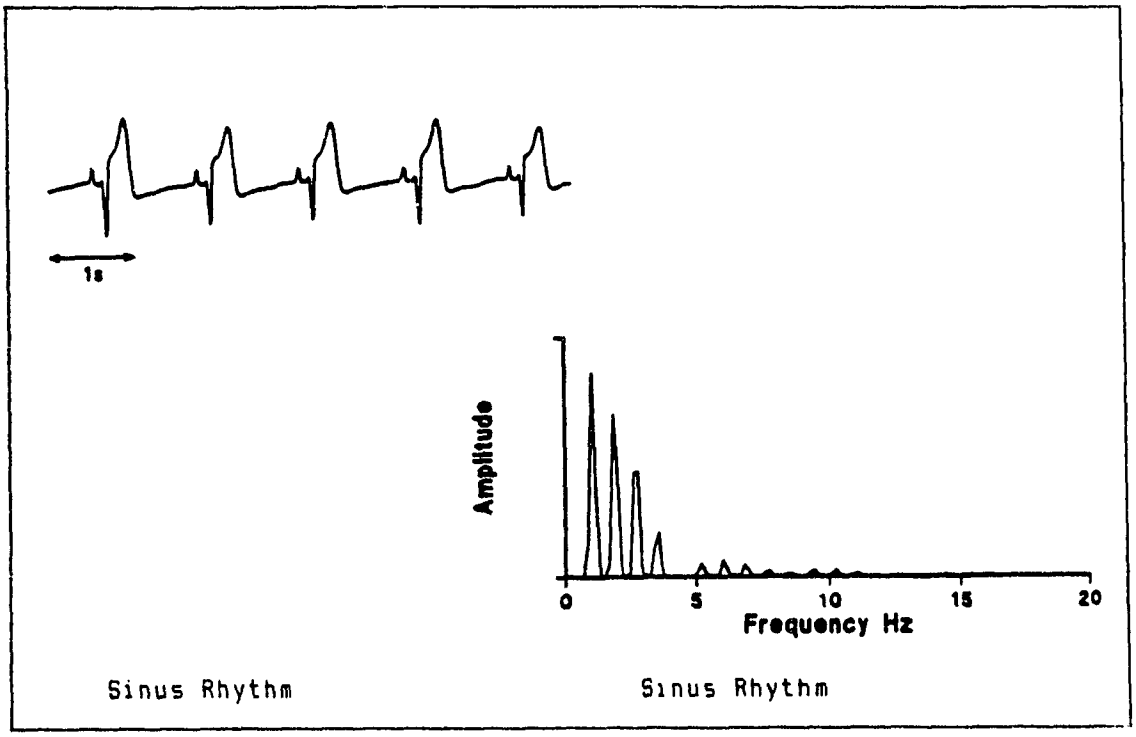


Fig. 3.2b - ECG rhythms in the time domain and power spectra of sinus rhythm. [7]

Widman's group used the Fourier power spectrum in the characterization of artifact and other anomalies [35]. They used the fact that baseline shifts show a predominance of power in frequencies below 2 Hz. High amplitude artifacts lack a prominent single peak frequency. Ventricular fibrillation has a major peak between 3.5 and 9 Hz. The range used by Widman's group in detecting VF is much wider. Figure 3.3 illustrates the power spectra of certain conditions.

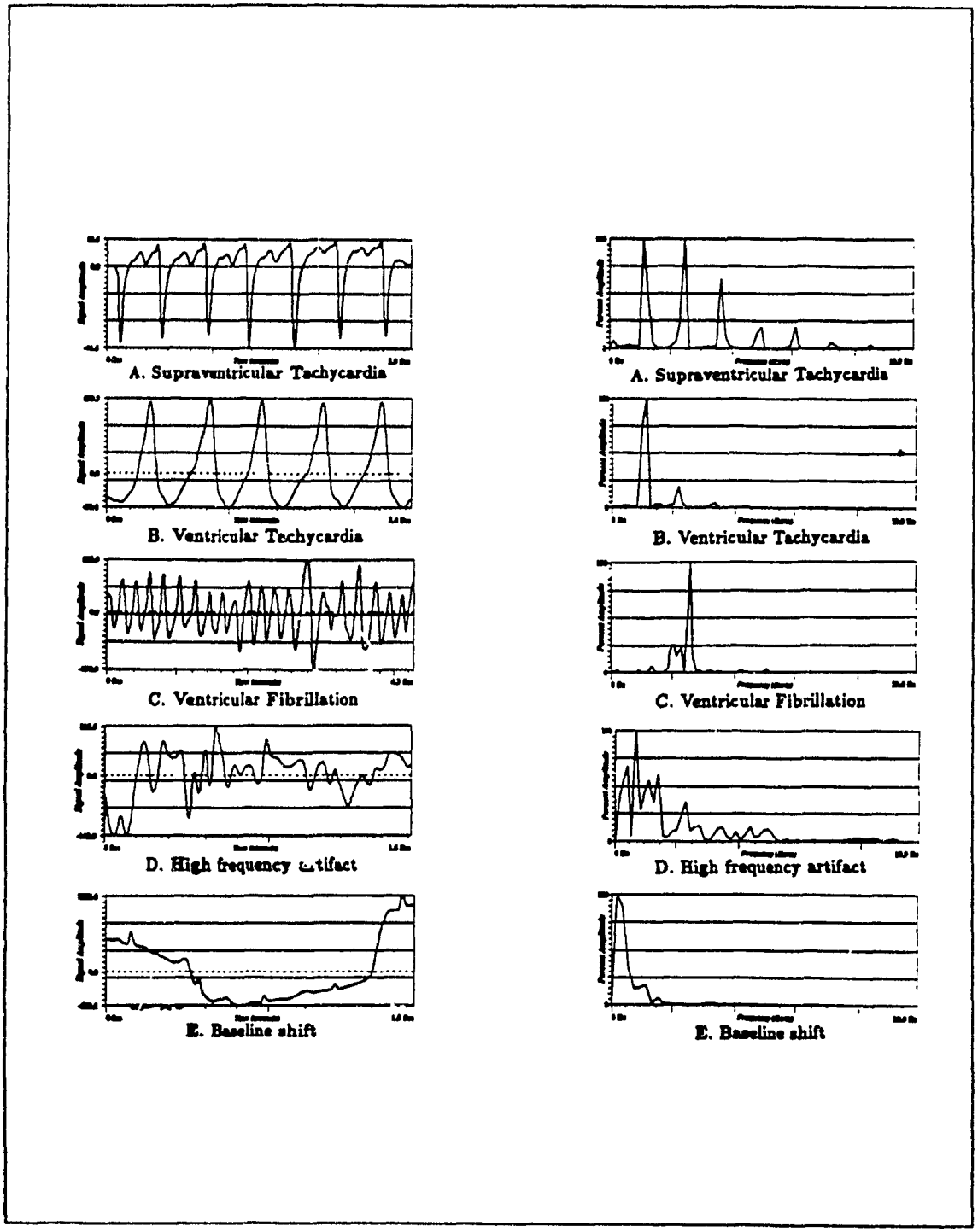


Fig. 3.3 - ECG rhythms in the time domain and Power Spectra. [35]

Signal filtering.

As discussed in section 3.2, the presence of artifact or "noise" can interfere in the classification of a waveform. It is useful to apply a filter to the original signal in an attempt to reduce the noise. One such filter is a "Direct Form II Transposed" implementation of the standard difference equation. The equation is the following:

$$y(n) = b(1)*x(n) + b(2)*x(n-1) + \ldots\ldots\ldots + b(nb+1)*x(n-nb)$$
$$- a(2)*y(n-1) - \ldots\ldots\ldots - a(na+1)*y(n-na)$$

where y(n) : filtered data

x(n) : original ECG signal

a(n) : first filter vector (can be a scalar)

b(n) : second filter vector (can be a scalar)

This is a simple calculation which passes the original signal through a filter in an attempt to reduce the noise. For best results it is best to choose a and b so that they add up to one.

Chapter IV

IMPLEMENTATION

4.1 - PURPOSE.

The purpose of this project is to develop software which will serve as a tool to a user, who is analyzing ECG signals. The user will have the option of applying various preset transformations to the original signals or even of developing his own transformations. The analysis done by the user is to detect abnormalities in the heartbeat as described in section 2. There are numerous transformations that can be applied to the ECG signal each returning different information, as described in section 3. A few have been incorporated in the system, but many more can be added by the user, as he sees fit.

4.2 - HARDWARE AND SOFTWARE USED.

The hardware used for this system consists of standard IBM AT 286/386 clones with VGA monitors and 8087 math co-processors. The reason for the 286 and 386 is that the software was developed on two computers, an AT 286 desktop and a 386 Samsung notebook. Due to the absence of a memory manager, 640K of memory is all the system had. The software was developed with this limitation in mind. An Epson FX-100 printer was used for hard copies. This ensured that no special hardware would be necessary to implement this system, making it more general and economical.

The software was implemented using TURBO PASCAL version 6.0 and MATLAB version 3.5g. PASCAL offers many built in procedures for graphics, which were deemed interesting. MATLAB offers numerous mathematical functions such as matrix manipulation, polynomial manipulation, statistical analysis and signal processing.

MATLAB has three versions for IBM and compatible personal computers: PC-MATLAB, AT-MATLAB, and 386-MATLAB. This project used PC-MATLAB due to its memory limitation. PC-MATLAB requires at least 320K of memory and a numeric co-processor. Even though the hardware utilized for this system is equivalent to an AT, the memory requirements of 2M of memory of which 1M byte must be extended memory, limited the use of AT-MATLAB. For this reason PC-MATLAB was used.

4.3 - THE SYSTEM.

Introduction.

This system is designed to be strictly off-line. It reads data from diskettes. All user input is done from the keyboard (no provision was made to accept choices from a mouse). All output is directed to the VGA screen. It is possible to obtain hard copies of any of the output directed to the screen through <Print-Screen>. Since we are using a VGA screen the DOS driver *GRAPHICS.COM* did not work. *GRAPHICS.COM* is appropriate for dumping CGA graphics to Epson dot-matrix printers. MATLAB comes with additional drivers for systems with EGA or VGA cards and Epson or Hewlett-Packard LaserJet printers. *EGAEPSON.COM* driver dumps EGA and VGA graphics to Epson compatible printers. *EGALASER.COM* driver dumps EGA and VGA grpahics to HP LaserJet compatible printers. They must be executed from the DOS prompt prior to involing any other software.

The illustrations in this report of the menus and the graphs generated by the system developed were possible through the use of *EGAEPSON.COM* and <Print-Screen>.

The data files used.

The Sample Data files used in this system are based on database tapes from the American Heart Association Database. Extracts of different sizes, from different tapes were made to allow for the testing and development of the system.

The original tapes are recorded on standard industry-

compatible nine-track tape. Each database tape contains four blocks: an ID block file, Sample Data file, Annotation and Time-Of-Occurence file, and a second ID-Block file. For the purpose of this system, only the Sample Data files were considered.

The Sample Data file contains the ECG sample data. The data was taken at 250 samples per second from two ECG channels. Samples have 12 bits of precision, and are stored in two 16-bit words with sign-extension. Data samples are two's complemented, stored least significant byte first, and its high byte written second. This requires the manipulation of the data before it can be used. Samples from each channel are stored alternately. Therefore when looking at the first channel need to consider every other word.

The data file looks like this:

Sample 1:Chan. 1
Sample 1:Chan. 2
Sample 2:Chan. 1
Sample 2:Chan. 2
.....

To convert the data back to a usable format it was necessary to swap the high and low order byte of the word. PASCAL has a swap function so this was very simple to perform. The resulting value was then "anded" with $FFF to eliminate the first 4 bits and convert the number to a

number with 12 bit precision.

Why use MATLAB?

MATLAB is a mathematical package which works with one kind of object, a rectangular matrix with possible complex elements. It allows matrix operations, array operations, vectors and matrix manipulation, data anlysis, matrix functions, polynomials and signal processing and graphing, in other words everything, required to analyze ECG signals. It was more interesting to incorporate an already existent mathematical package than to rewrite many of the functions from scratch. The use of MATLAB offers, to the user, more choices in the algorithms that he can develop.

Behind the scene: The PASCAL and MATLAB interface.

The first version of the system was quite different from the final one. It was at first written as one large program, with a small main part and numerous subprograms. The call to MATLAB was done from within one of the procedures. Due to the 640K memory limitation, there was not enough memory to load both the PASCAL program and MATLAB. The next step was to break down the PASCAL program into smaller programs, and have a small "driver" program calling each smaller program in turn as well as MATLAB, thus having more memory free at any one time. This was implemented with the EXEC command in PASCAL. The software was developed as a menu driven system in order to make MATLAB as transparent to the user as possi-

ble.

MATLAB offers the possibility of writing script files thus reducing the need of the user to interface with MATLAB itself. However these script files can be invoked only from within MATLAB. This was the largest limitation of this software. When the PASCAL program calls MATLAB, the user is required to type in the name of the script file. It is not possible to call MATLAB and give the name of a script file to be executed at the same time. The interface between the two programs is done so as to minimize the user's involvement. Before calling MATLAB, the PASCAL program creates a file with all the parameters needed by MATLAB to perform the transformations selected by the user. The script file terminates the session with MATLAB and returns to the main PASCAL program which continues to "drive" the system.

The system "*driver*".

The system driver is the heart of the software. It controls the flow of operation and executes the appropriate calls to the necessary programs. It begins by a call to the banner program, which is the welcome screen. The next call is to the menu program which is where the user selects his options. If the user has not decided to quit, the system will then invoke the Firstscreen program which creates the first data file to be transformed and graphed. The driver goes on to call MATLAB to perform the transformations required and then the graph program to graph the original signal and the requested transformations. Once the graph is displayed, the user decides whether to window right, left, extract a portion of the ECG on screen for further analysis, or quit. If the user decides to window left or right, then the next screen of information is stored in a data file and the driver loops back to the MATLAB call. If the user decides to quit, he is brought back to the first question where he can quit the system or go on to setting new options. Finally if the user decides to extract a section of the current screen for further analysis, then the information is stored in a new data file, and MATLAB is then invoked. The user will have a choice of menu items or the options of working MATLAB on his own. The results are graphed from within MATLAB. Once the user has finished his session with MATLAB he is brought back to the full screen from which he decided to extract a segment and is asked

again whether he wishes to window extract or quit. Once the user decided to quit the system entirely, a cleanup program is called to erase all the temporary data files created by the driver to pass parameters from one program to the next.

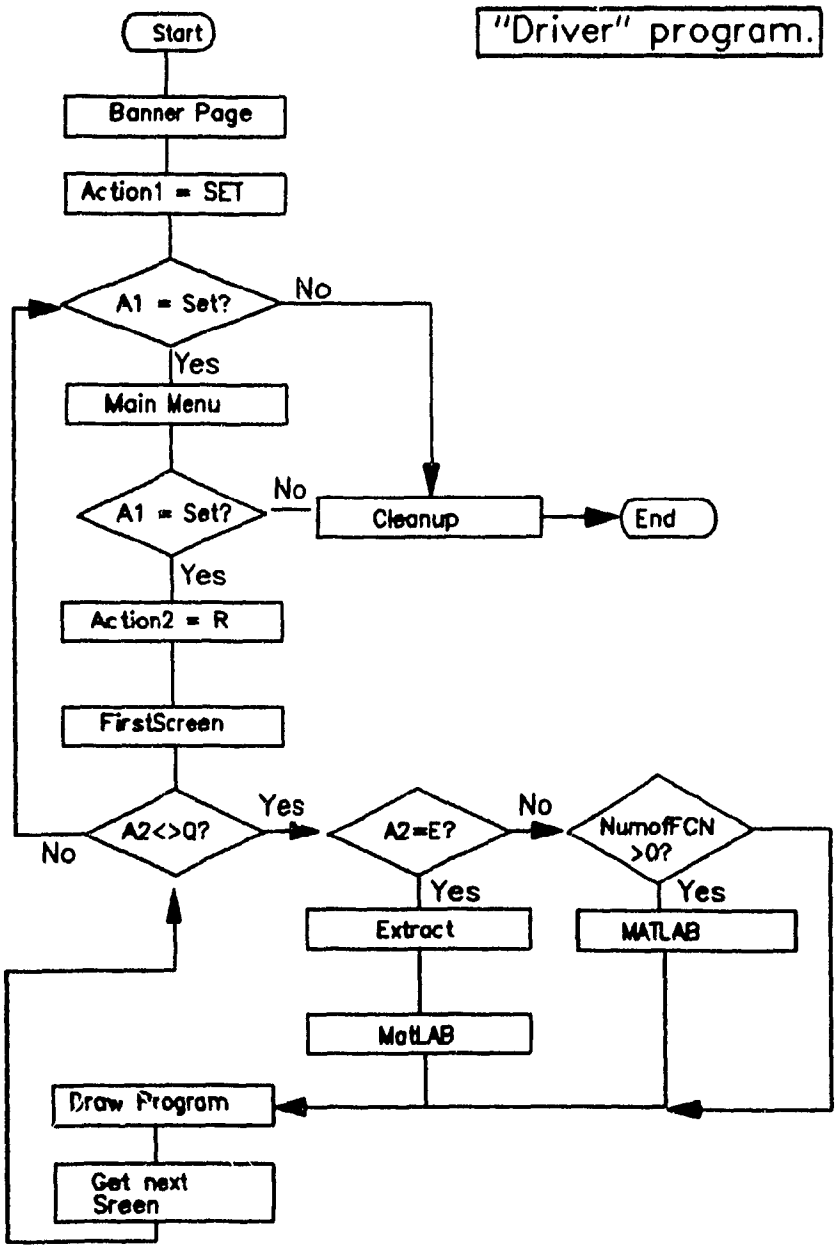


Fig. 4.1 - Flow diagram of system "driver".

The system: Components of the system.

Banner program.

The user interface is designed to be as user-friendly as possible, and as pleasant to the eye as possible. It begins by welcoming the user to the ECG system with an identification screen. As part of the screen there is an ECG graph of about 200 points incorporated, where the sample data is taken from one of the data files available to this system. Once the return key is hit, the banner program is terminated.

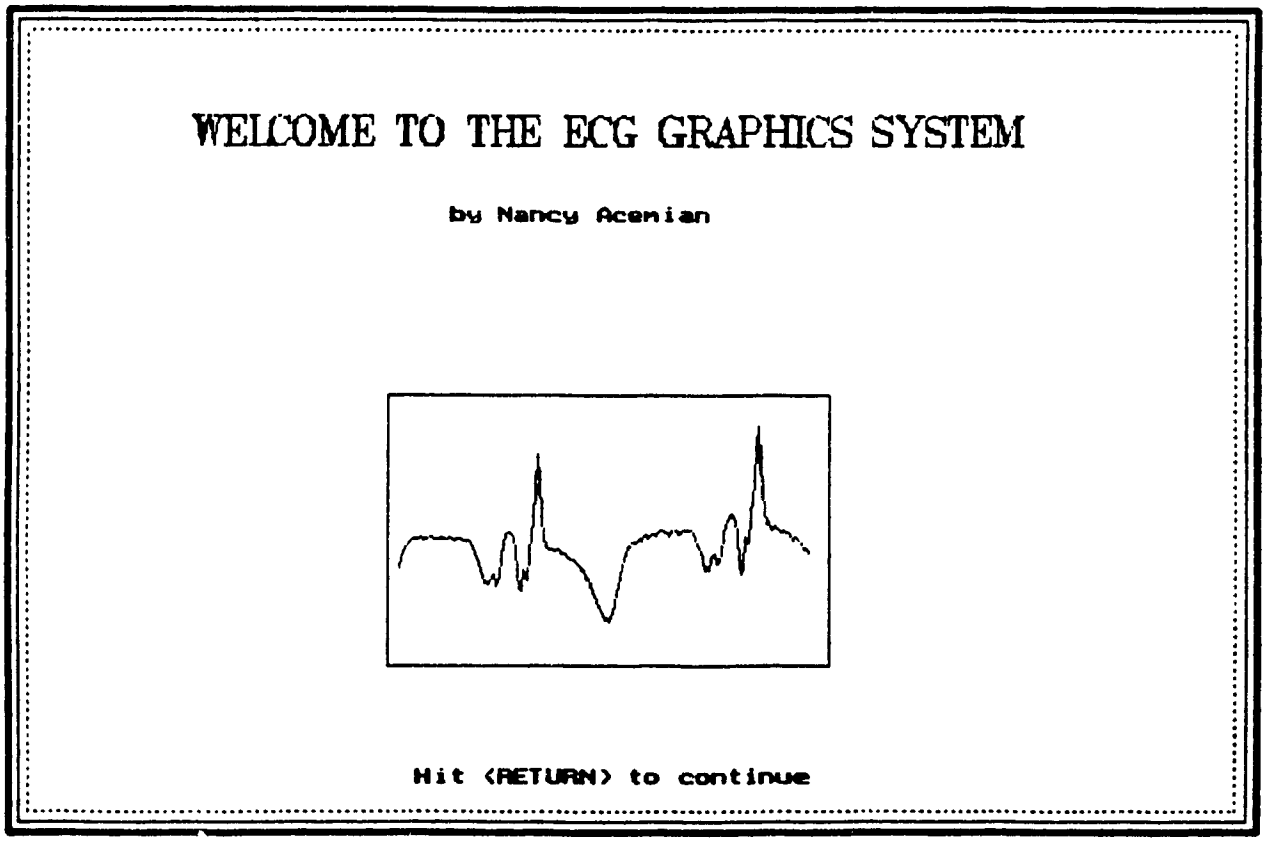


Fig. 4.2 - Welcome screen.

Menu program.

The next program to be called is the MENU program. It begins by asking the user whether he wishes to set parameters or quit the system; the system is designed in such a way that the user can at any level of the system decide to quit and will be brought back to this level. Refer to figure 4.4 for a flow diagram of the menu driver. The user has the option of terminating the session or resetting the options.

For the system to accept and understand the input from the keyboard, it is necessary to type a command as instructed by the program and to hit 'return'. At this point, no default option is set by the software, if 'return' alone is pressed. This may be added at a later date.

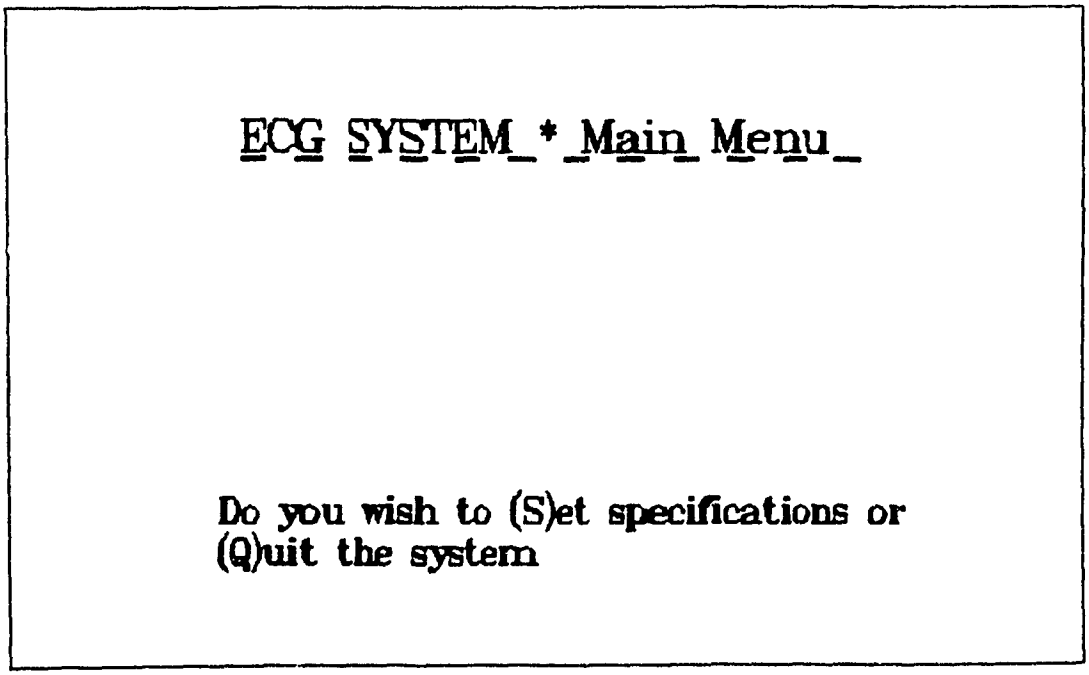


Fig. 4.3 - Main menu

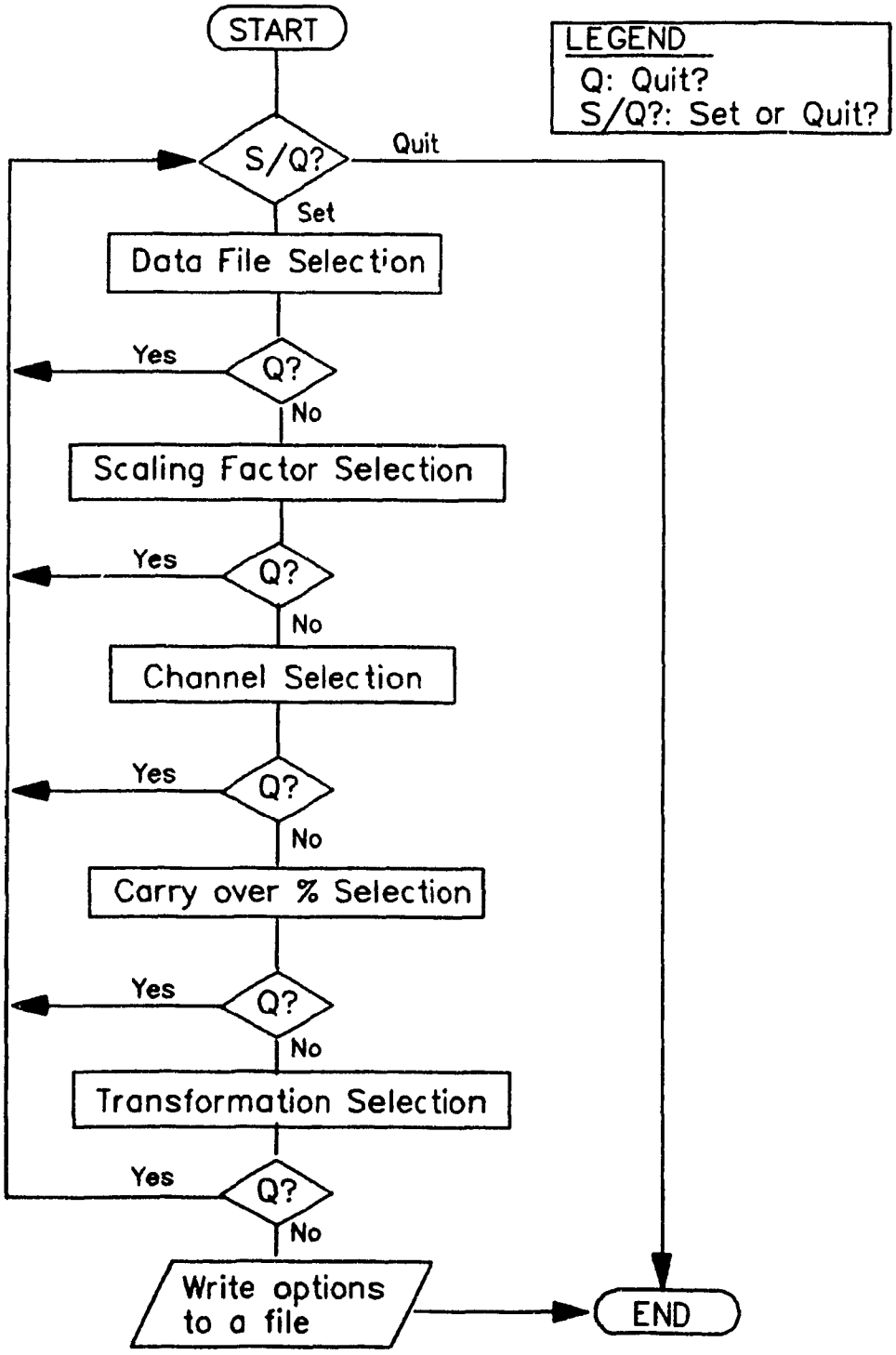


Fig. 4.4 - Flow diagram of main menu driver

Data file selection.

Once the user decides that he wishes to set the parameters, he is prompted for the data file he wishes to view and analyze. He has the option of selecting preset data files or selecting one of his own. When selecting one of his own, he must specify the full pathname of the file as well as the full name of the file. The system will then proceed to validate this file name. It will make sure that is can access it. If it is unable to link to it, it will instruct the user that his choice was not valid and that he must select a new one. Once a valid file is found, the system will open the file and position the pointers at the beginning of the file.

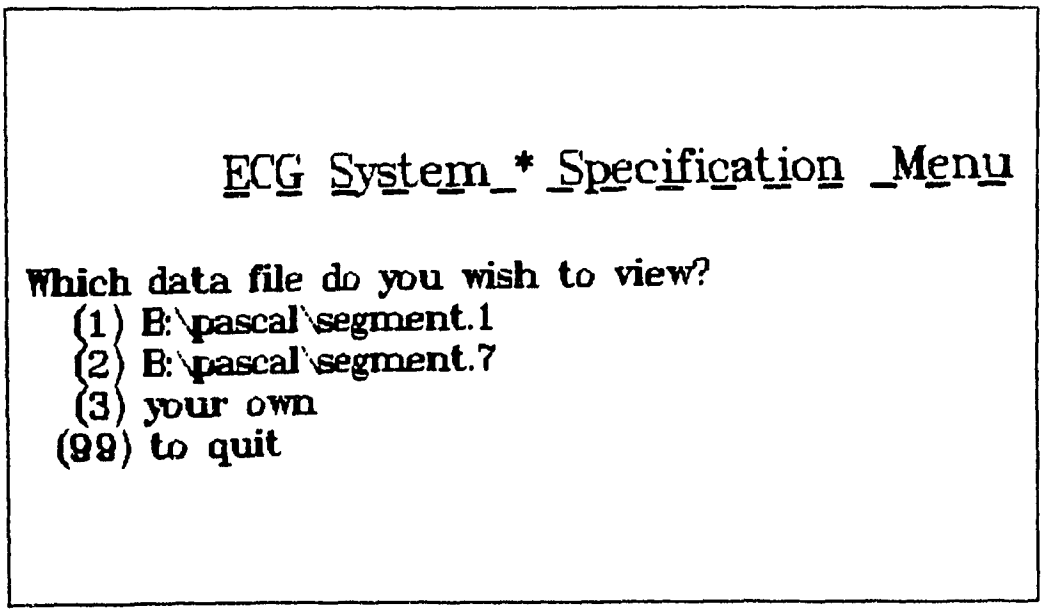


Fig. 4.5 - File Selection Menu.

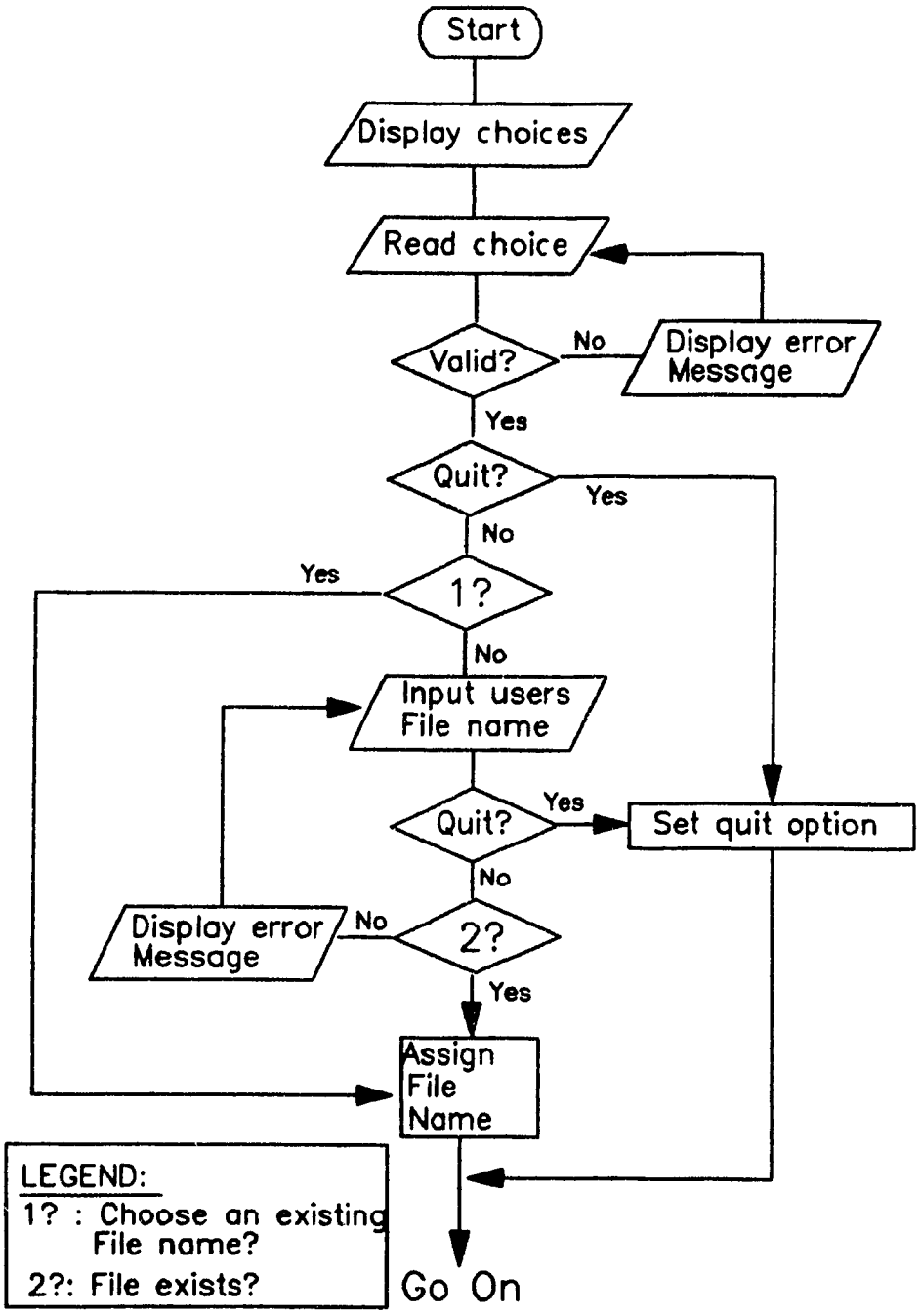


Fig. 4.6 - Flow diagram of File Selection

Scaling factor.

The next parameter to be set is the scaling factor. In other words does the user wish to have every point of a channel graphed, every second point or every third point. The advantage of looking at less points is that more beats can be viewed on a same screen. It was noted through testing, that three points was the maximum, because with more points, the shape of the waveform is altered and does not reflect the true story. When every second or third point is graphed, the screen is still filled. Therefore the less points are viewed, the less screens are required to view all the data.

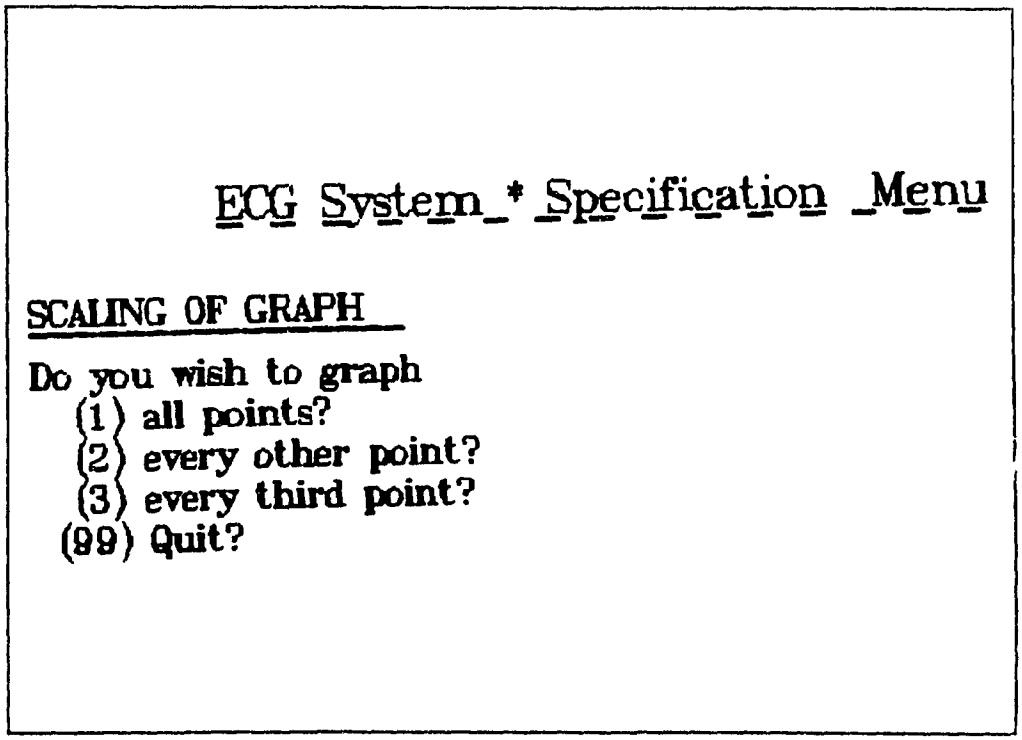


Fig. 4.7 - Scaling Factor Menu.

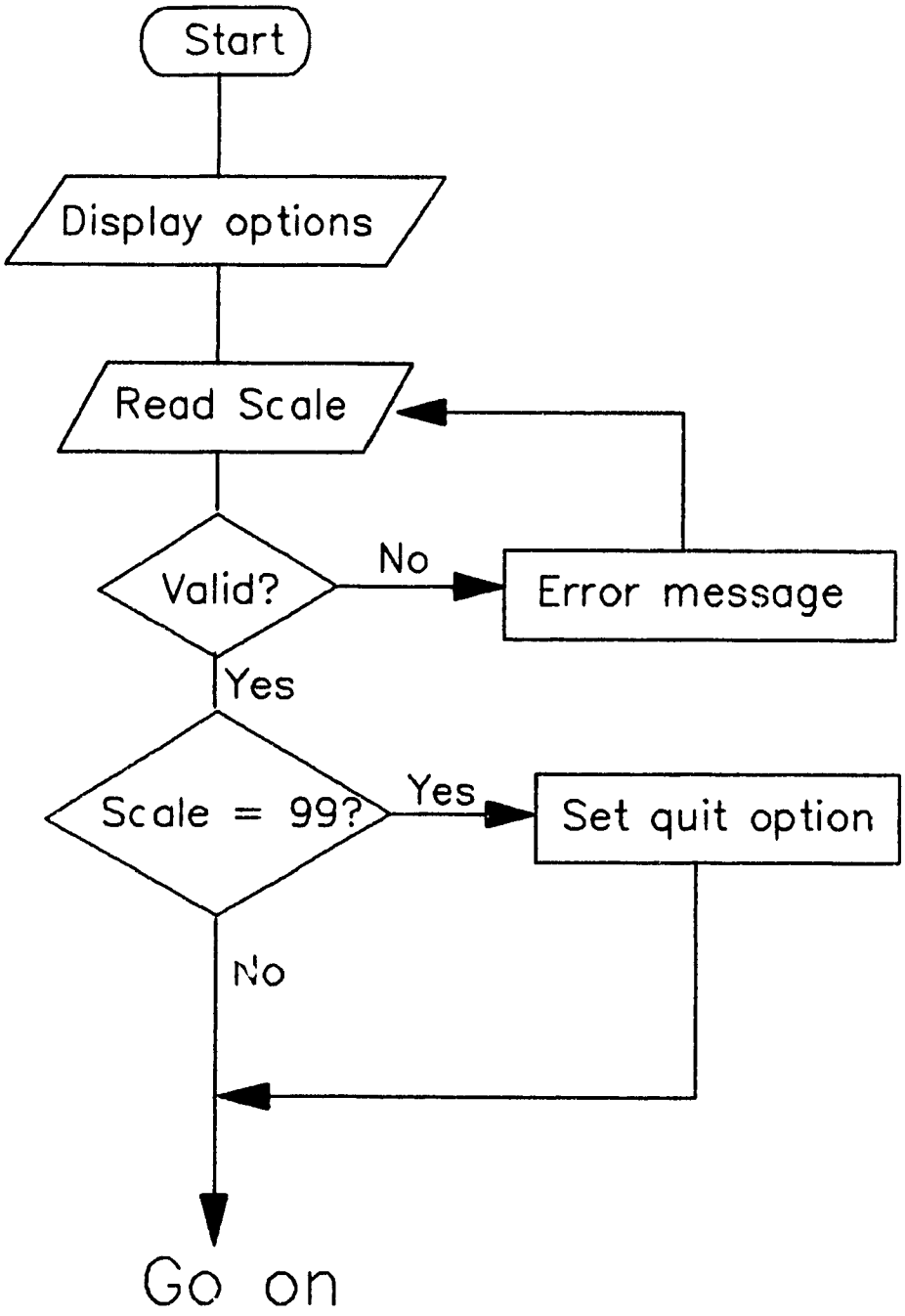


Fig. 4.8 - Flow diagram of Scaling factor selection

Channel Selection.

In this submenu, the user has the choice of viewing the first or second channel. If the user selects the second channel, then the system is initialized to the first point of the second channel as the beginning of the data samples.

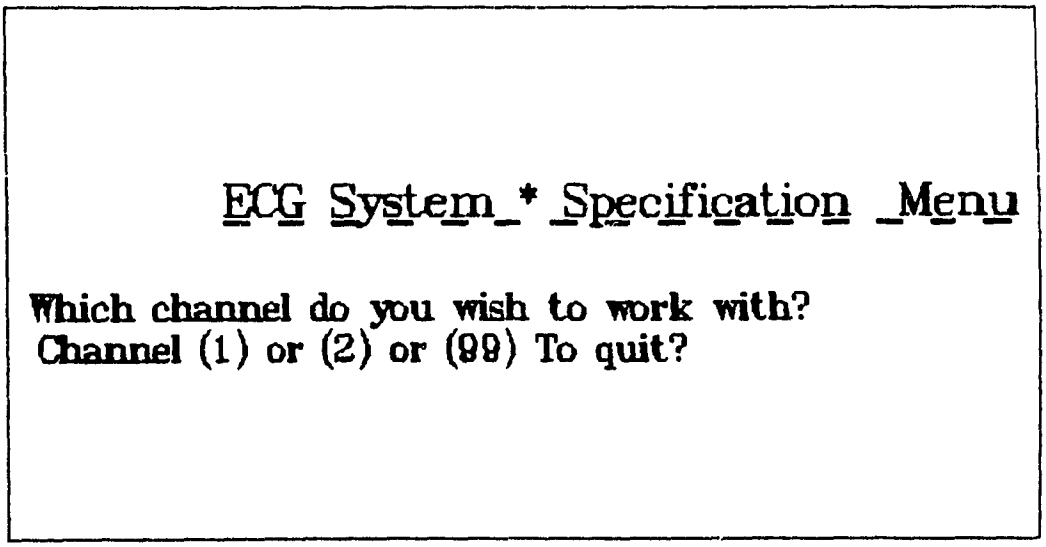


Fig. 4.9 - Channel Selection menu.

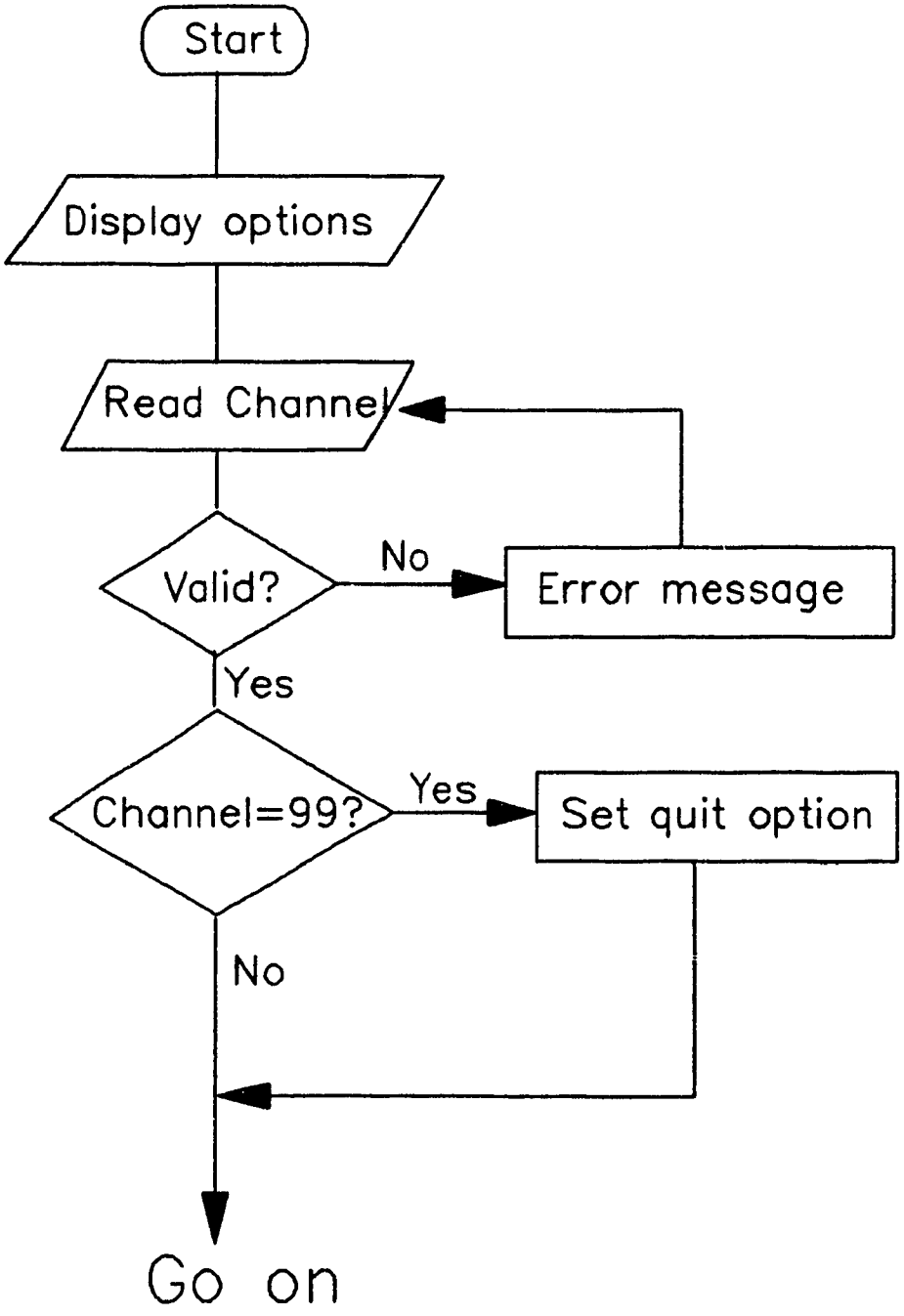


Fig. 4.10 - Flow diagram of channel selection

Percentage of screen to carry over.

This submenu allows the user to decide how much of the current screen to carry over to the next screen. The user has the choice of carrying over 0% to 80% of the current points to the next screen. In other words, if the user selects 33%, when he windows for example right, the next screen will contain the last third of the current graph followed by two thirds of new data. This applies regardless of the scaling factor selected.

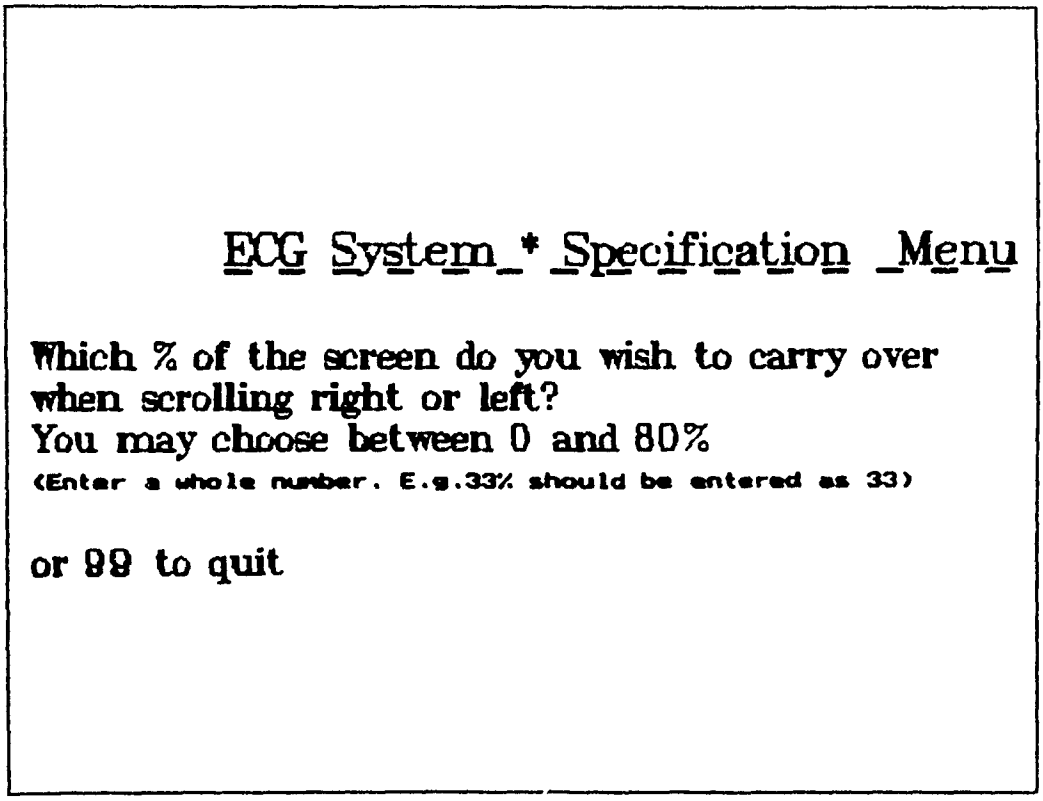


Fig. 4.11 - Percentage of screen to carry over menu.

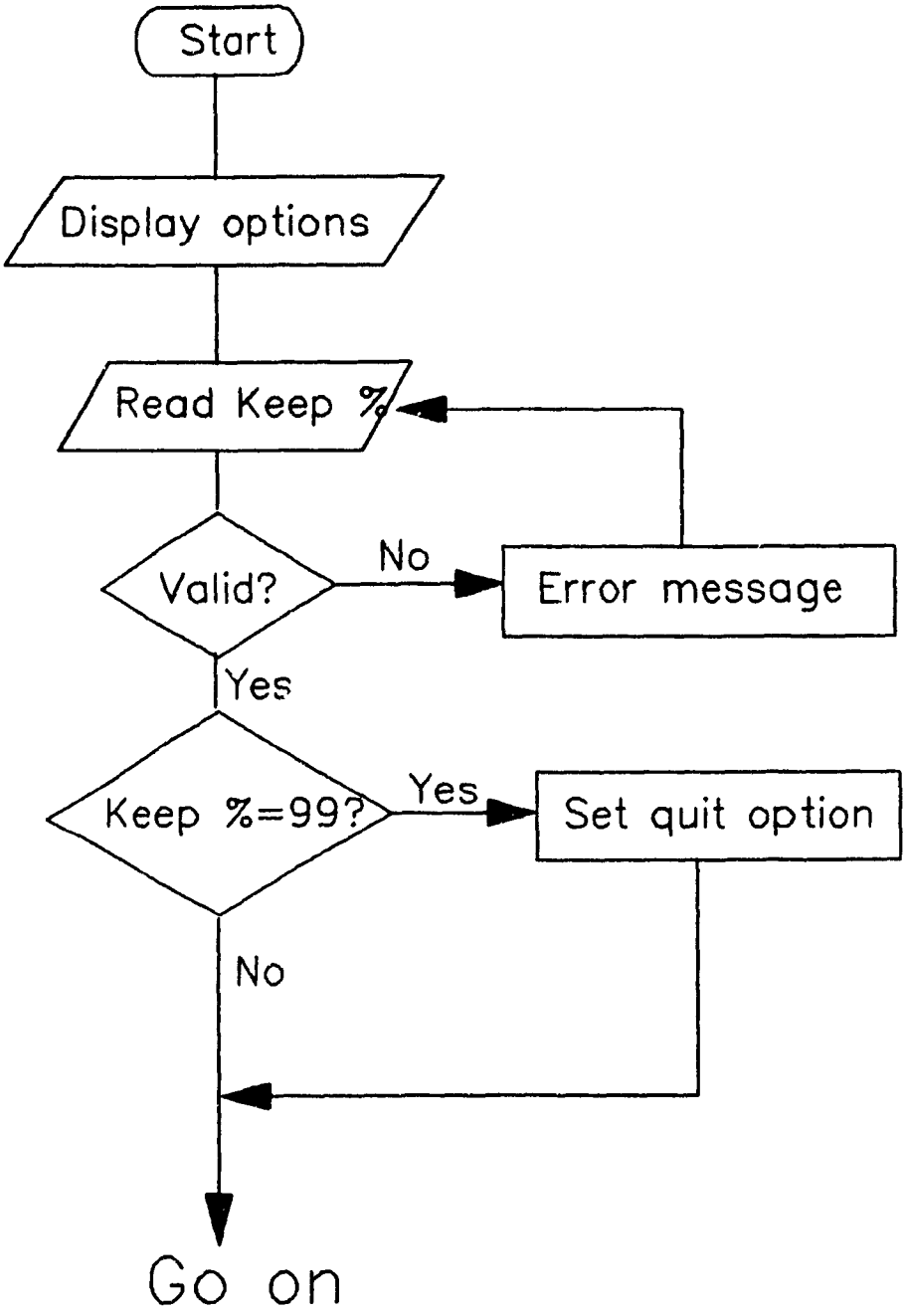


Fig. 4.12 - Flow diagram of carry over % selection

Choice of transformations.

This is where the "analysis" part of the system comes in. The user has the choice of viewing the sample data as is, applying one or even two transformations to the data. The transformations available, are a Fourier Transform, a first and second difference, beat detection based on the second diference as discussed in section 3.3, and filtering of the ECG signal based on the filter algorithm available in MATLAB discussed in section 3.4.

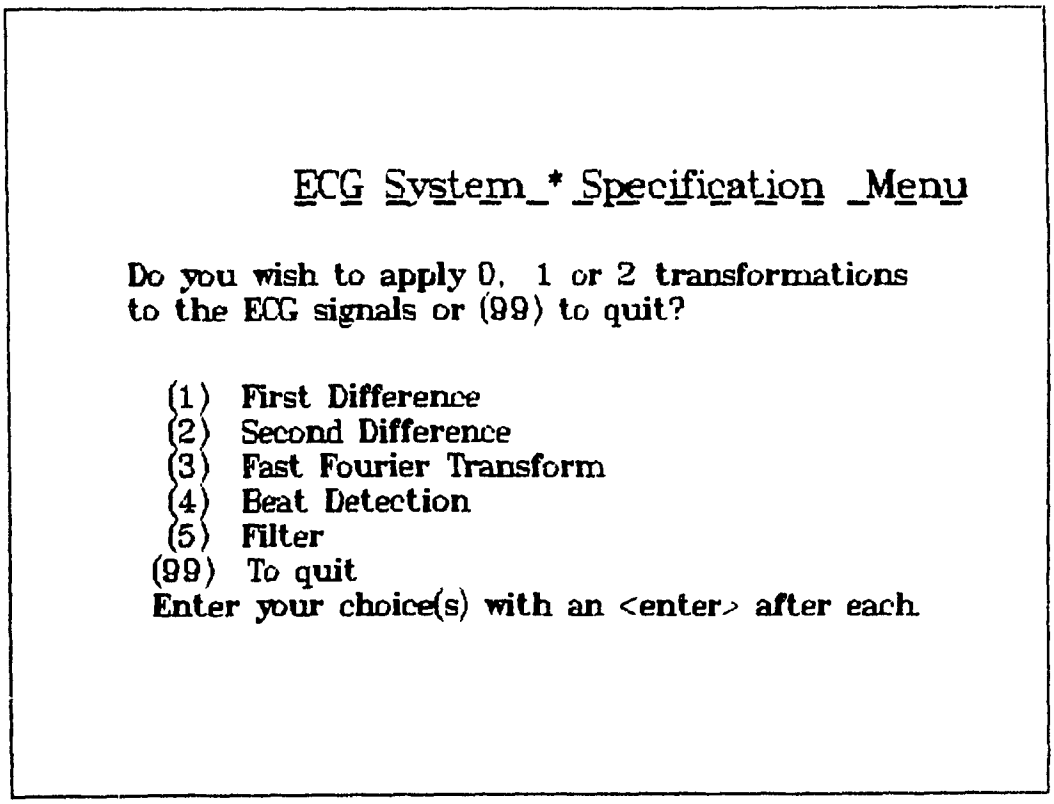


Fig. 4.13 - Transformation Selection Menu.

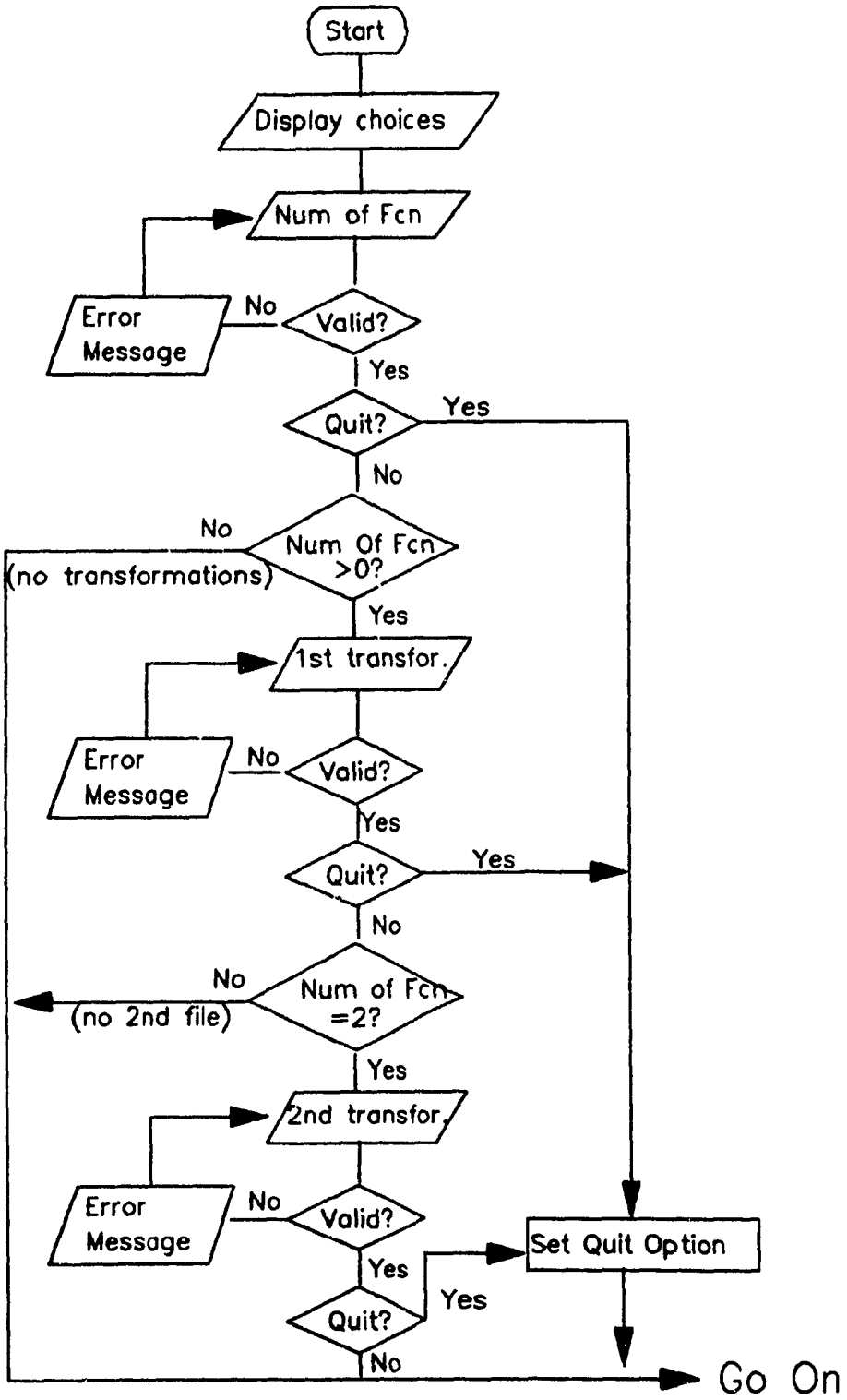


Fig. 4.14 - Flow diagram of transformation selection

Closing comments on the menu program.

The information carried over to the following sub-programs are the name of the data file containing the ECG signal, the scaling factor, the channel to be viewed, the percentage of the screen to carry over from window to window, the number of transformations and the transformations if any. A second temporary file contains the final action selected, that is whether selections were made or if the user decided to quit.

First Screen program.

This program will create the data file containing the first N signals, that is one screen full of ECG signals. It will take into consideration the scaling factor and the channel selected. Before terminating it will set the pointer in the original file from which it extracted the first screen full of information to the N+1th point.

The ECG Script file.

The script file in MATLAB begins by loading the ECG subset file to be processed. Then based on the number of transformations selected and which transformations, it will create temporary data file for the result of each transformation. The data files created are all preset and prenamed by the programmer. The only input required from the user at this level is to enter the name of the script file at the MATLAB prompt from within MATLAB, which is *ECG*.

Draw Graph Program.

The draw graph program displays the results in graph form. Based on the number of functions selected and the transformations themselves, it will draw preset data files corresponding to each transformation with the corresponding titles. If there are no transformations selected, Draw Graph will display the original ECG signal on the upper third of the screen, with a title. If one transformation is requested, it will add the graphical representation of the results in the second third of the screen along with the transformation name. Similarly if two transformations are requested, it will display the results of the second transformation in the lower third of the screen. Once the user has examined these graphs and wishes to continue, he just has to hit enter. This will terminate the Draw Graph Program. Refer to figures 4.16 to 4.18 for examples of each type of screens.

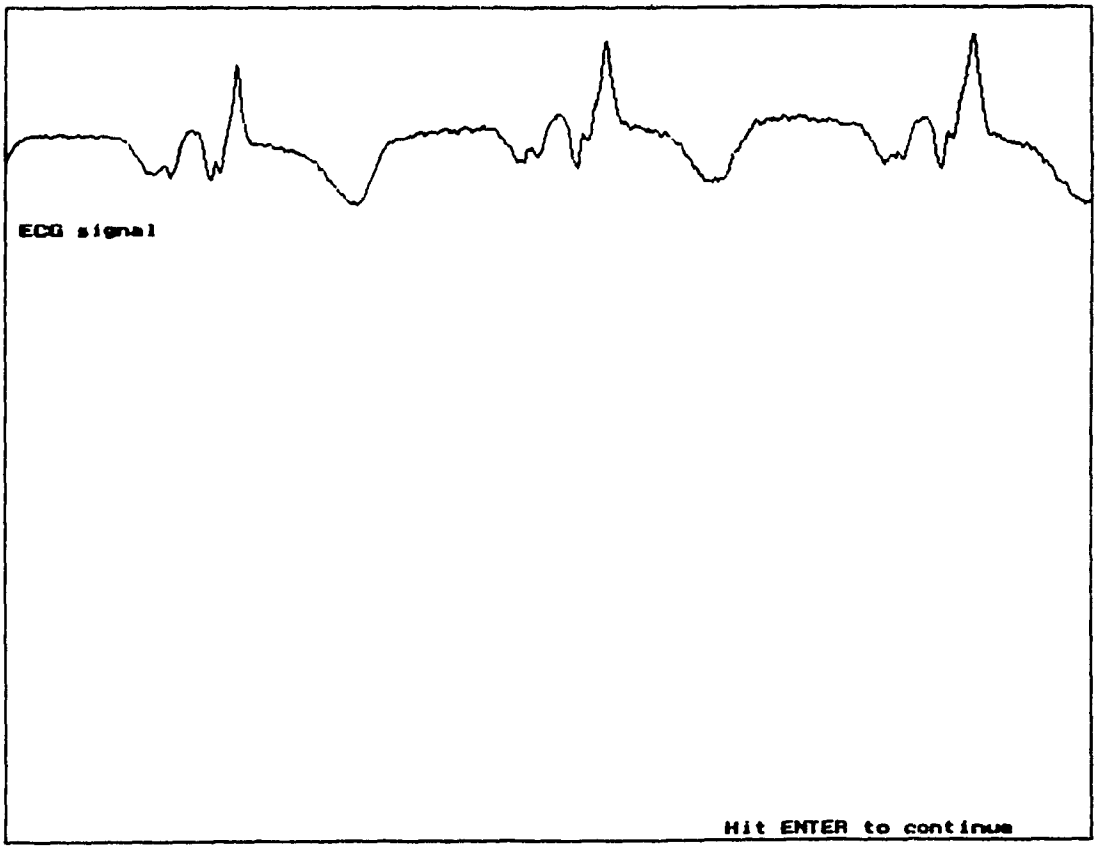


Fig. 4.16. - Example of original ECG signal.

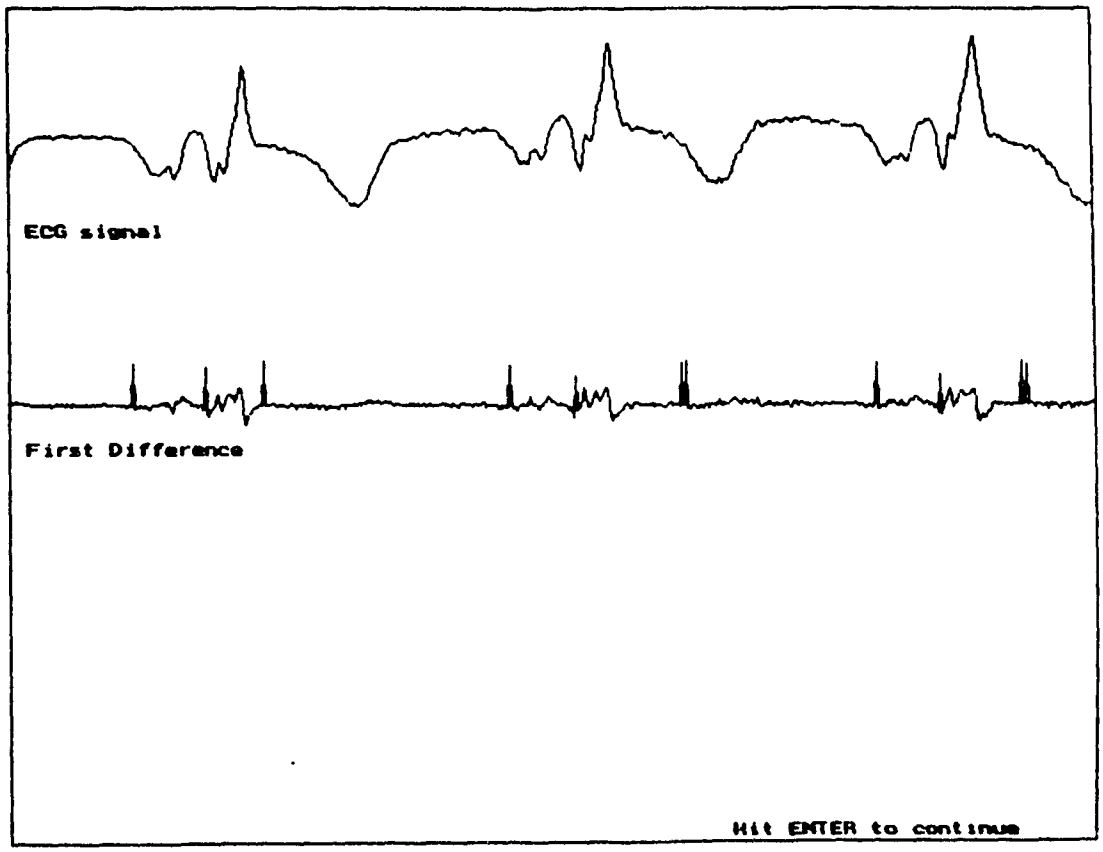


Fig. 4.17 - Example of ECG signal and one transformation

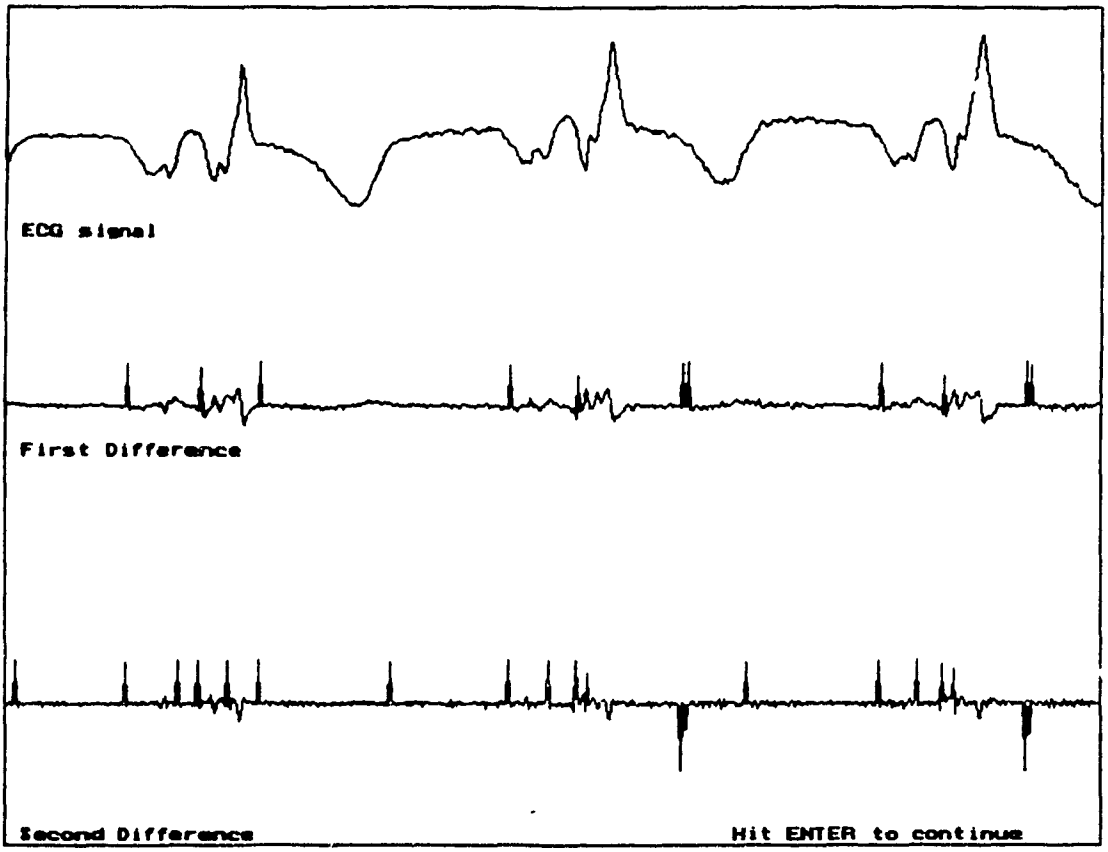


Fig. 4.18 - Example of ECG signal and two transformations.

Get Data Program.

This program is always called after the Draw Graph program. It asks the user what to do next. The possibilities are window right, window left, extract a section of the current screen or quit. If the quit option is selected the program is terminated and the driver will loop back to the main menu, where he can quit the system or reset the options. If the extract option is requested, then the Get Data program is terminated and the Extract Program takes over. Finally, if either of the windowing options are selected, the system will update the points to be graphed taking into consideration the direction of the window requested, the scaling factor, the percentage of the screen to carry over and where the previous screen ended. If the user's selection results in going pass the beginning of the file or the end of the file, an appropriate message is sent to the user, and he is prompted for a new choice.

```
Do you wish

   -- to window (R)ight
   -- to window (L)eft
   -- (E)xtract a portion of this screen for further analysis
   -- (Q)uit?

Please enter your choice followed by <enter>
```

Fig. 4.19 - Get Data Menu.

Extract Program

The Extract program will begin by displaying the ECG signal on the screen and request from the user the starting position and ending position of the segment to be extracted by moving the cursor. The system will extract 256 or 512 points, since most transformations in MATLAB work best with or require a power of 2 points. The system will then make a call to MATLAB where a script file will have to be called. This script file will be a menu, with preset options. The user will also have the option of manipulating the extracted segment on his own in MATLAB. If he chooses one of the preset options from the menu, then the script file will take care of issuing all of the commands. The plotting for the extracted data and its results will be done through MATLAB. Once the session is completed, the EXTRACT program is terminated and control returns to the driver. Refer to figures 4.20 and 4.21 for illustrations of the extract screen and confirmation screen.

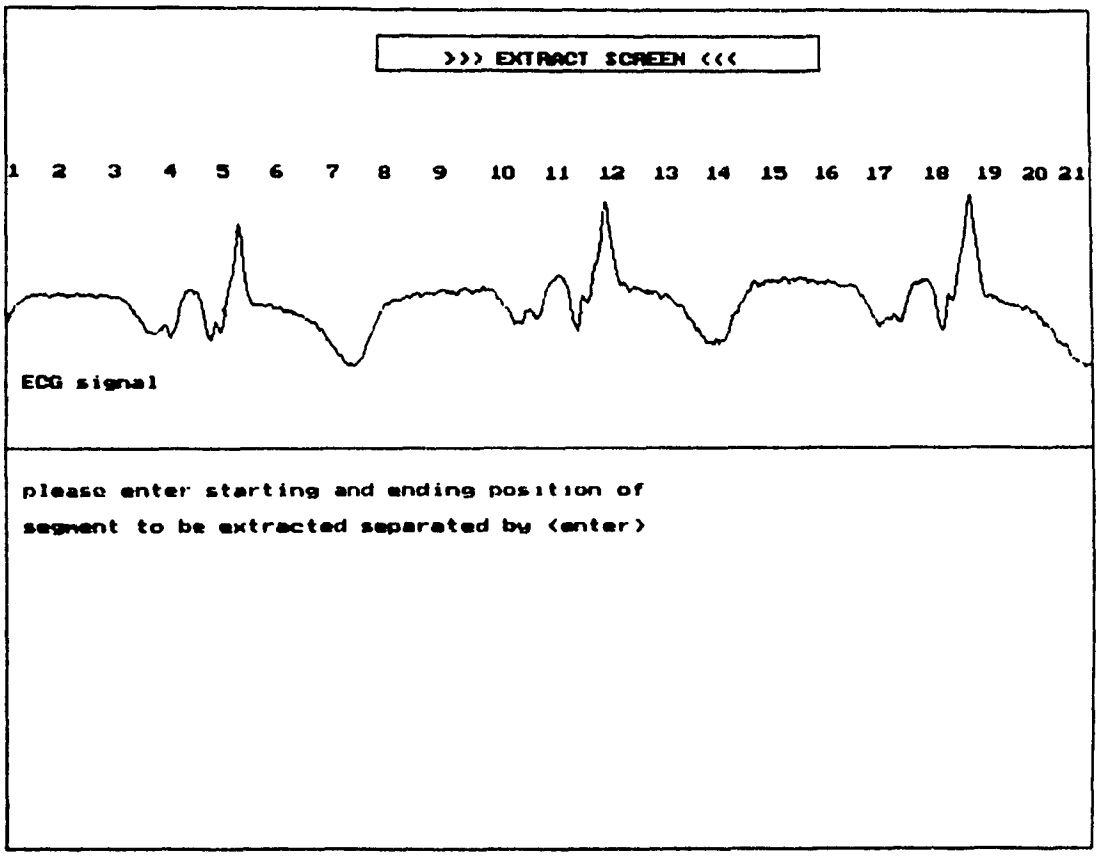


Fig. 4.20 - Extract screen

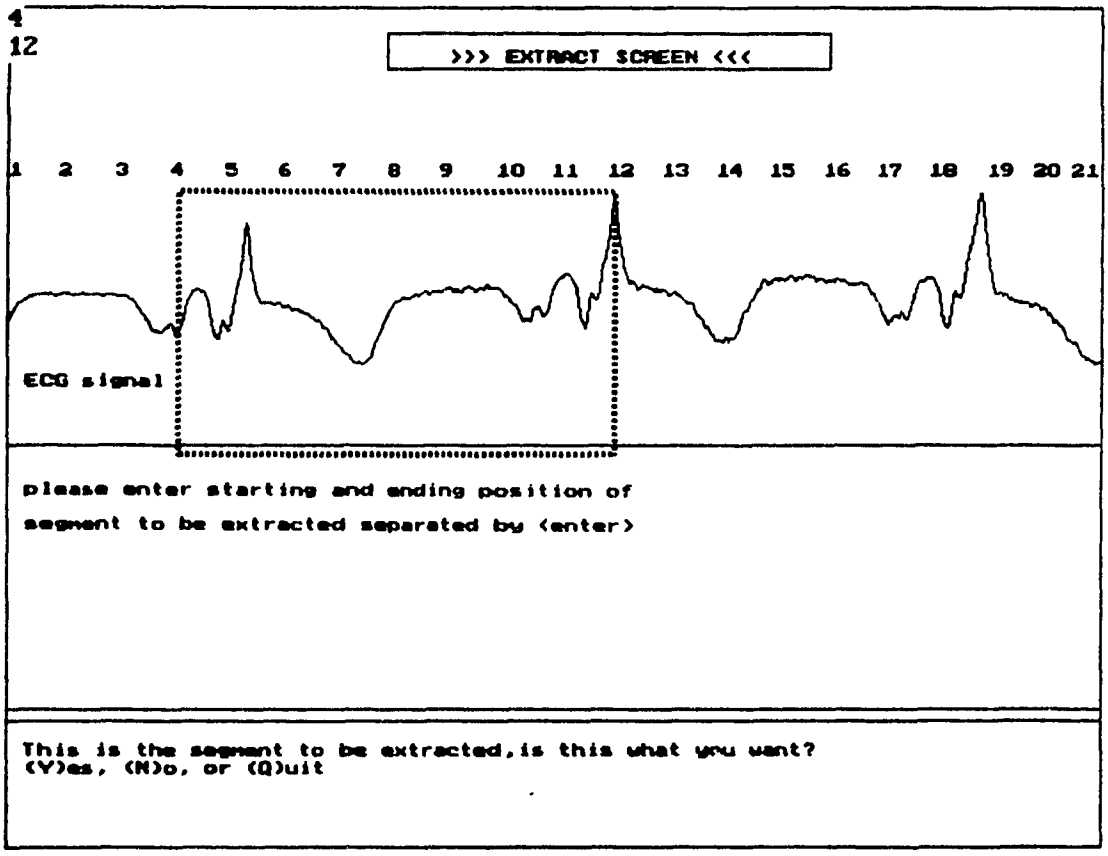


Fig. 4.21 - Confirmation of extracted segment.

Extract Script File.

The extract script file in Matlab begins by loading the file containing the extracted segment. It then presents the user with a menu asking him which transformation he would like to apply and plot. The user has the choice of going into "free-mode". This allows the user to enter his own MATLAB commands, assuming he is familiar with the software. A summary of the functions available and the plotting commands is supplied in appendix A. It is up to the user to quit out of MATLAB. Following are examples of graphs produced by the Extract segment of this software through MATLAB and the menu the user sees.

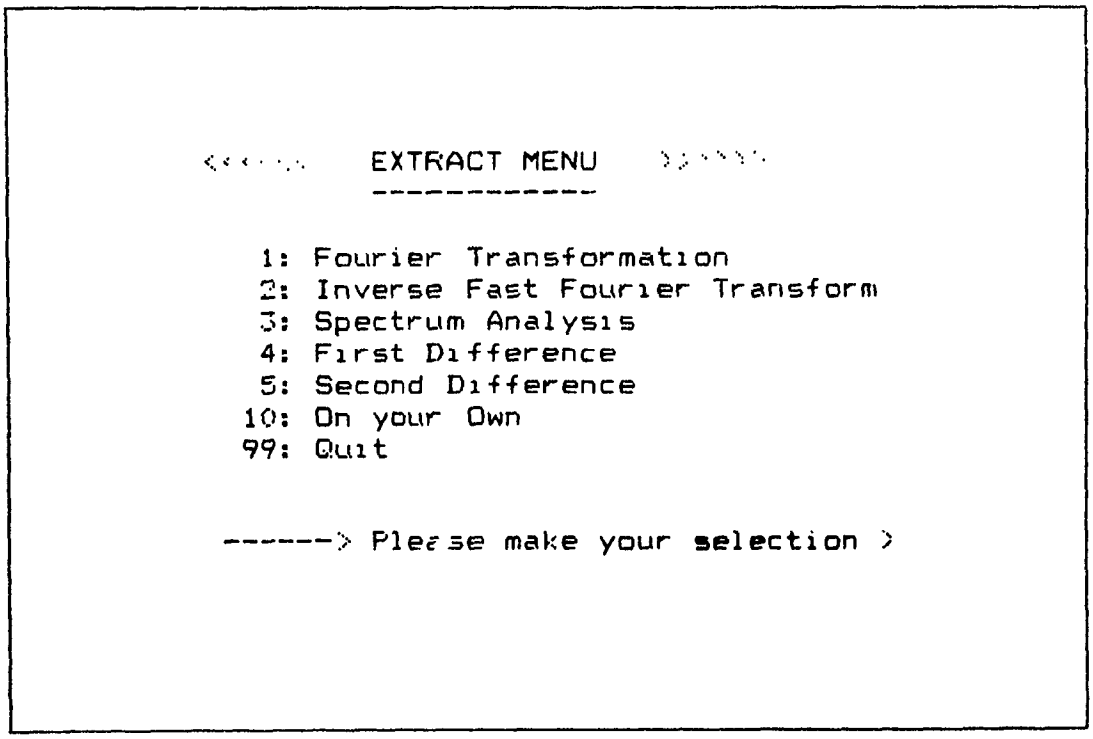


Fig. 4.22 - Extract Menu

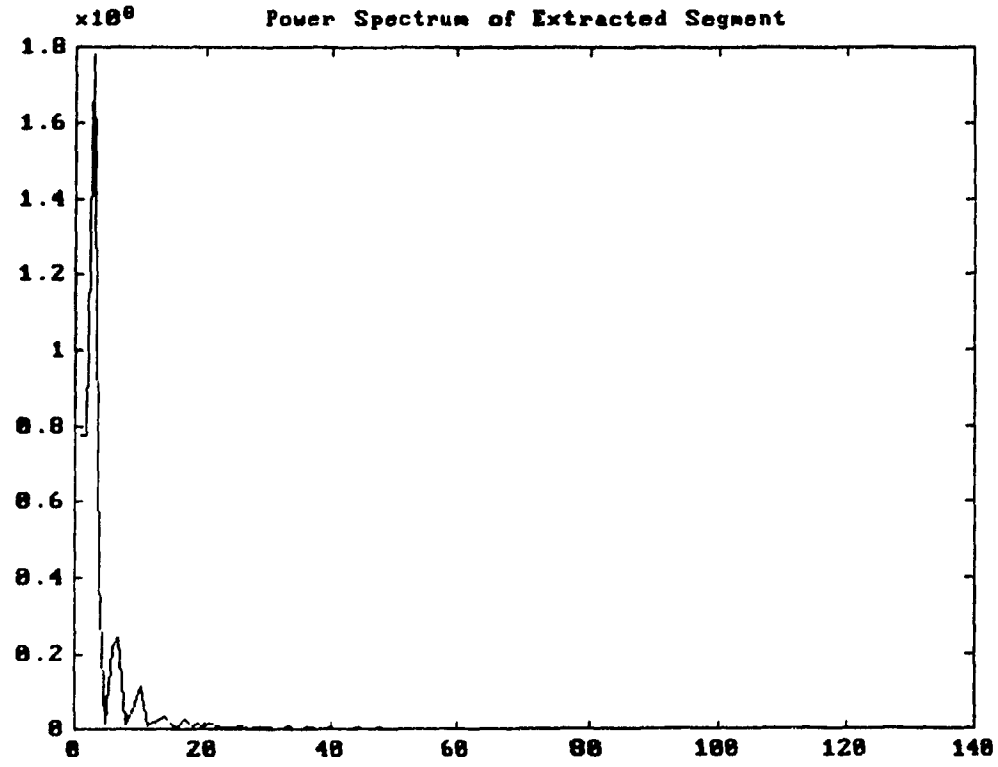


Fig. 4.23 - Example of Power Spectrum of Extracted segment.

Cleanup Program.

The cleanup program is the last program to be called before the system terminates. It is called when the user has asked to quit the system. All temporary files created by the system are erased. The code is written in such a way as to check whether each file exists before attempting to erase it.

Chapter V

DEMONSTRATION OF FEATURES

In the previous chapter an elaborate description of the system in question was given. In this section some of the features will be illustrated.

5.1 — SCALING OF ECG SIGNAL.

The first feature is the scaling of the ECG signal, where the user has the choice of graphing every point, every second point or every third point. When every point is graphed, there are approximately three R-R intervals per screen. Needless to say, when every second point is graphed there will be six R-R intervals and when every third is graphed, there will be nine R-R intervals. Figures 5.1 to 5.3 demonstrate this well. In the three screens the graphing is done with the same starting address in the file. The first three R-R intervals in the second screen, figure 5.2, are the same as in the three in the first screen, figure 5.1. The first six R-R intervals in figure 5.3 are the same as the six in figure 5.2. This is a useful feature, when it is necessary to view the shape of successive R-R intervals, instead of analyzing the shape of a particular one.

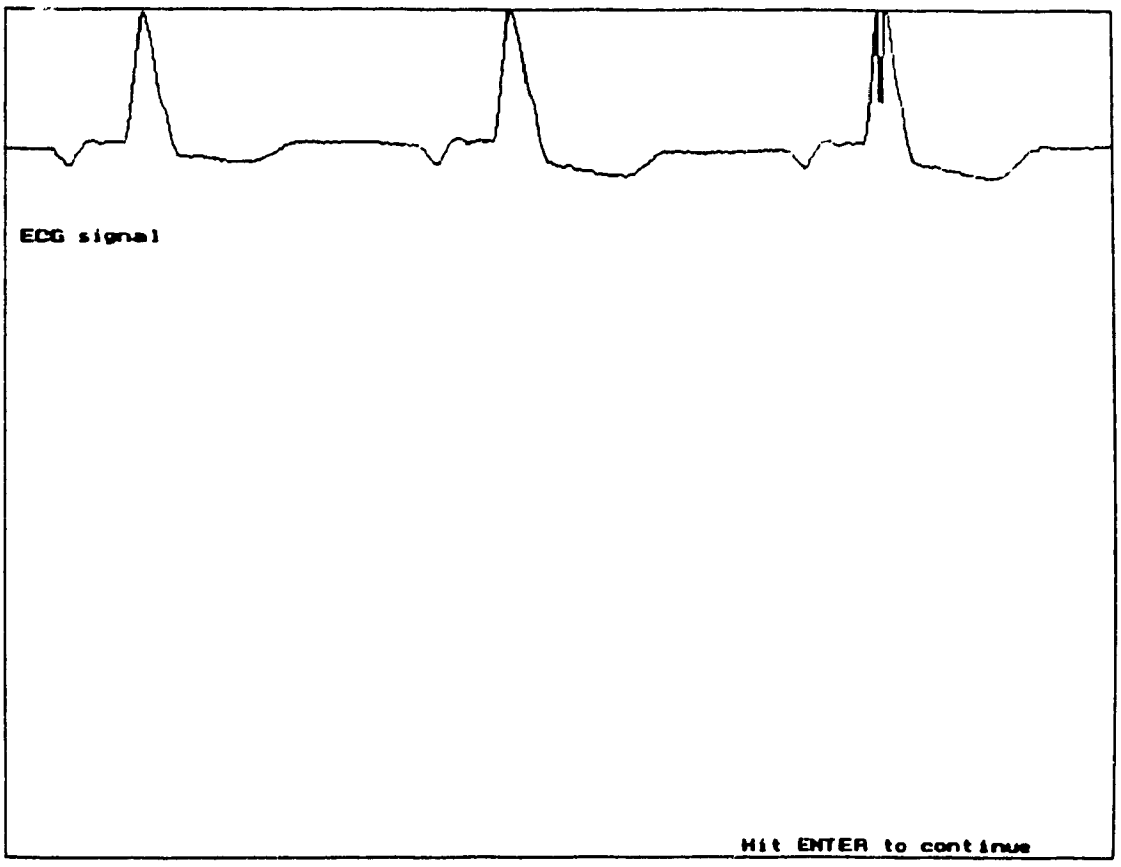


Fig. 5.1 - Example of ECG signal with every point graphed.

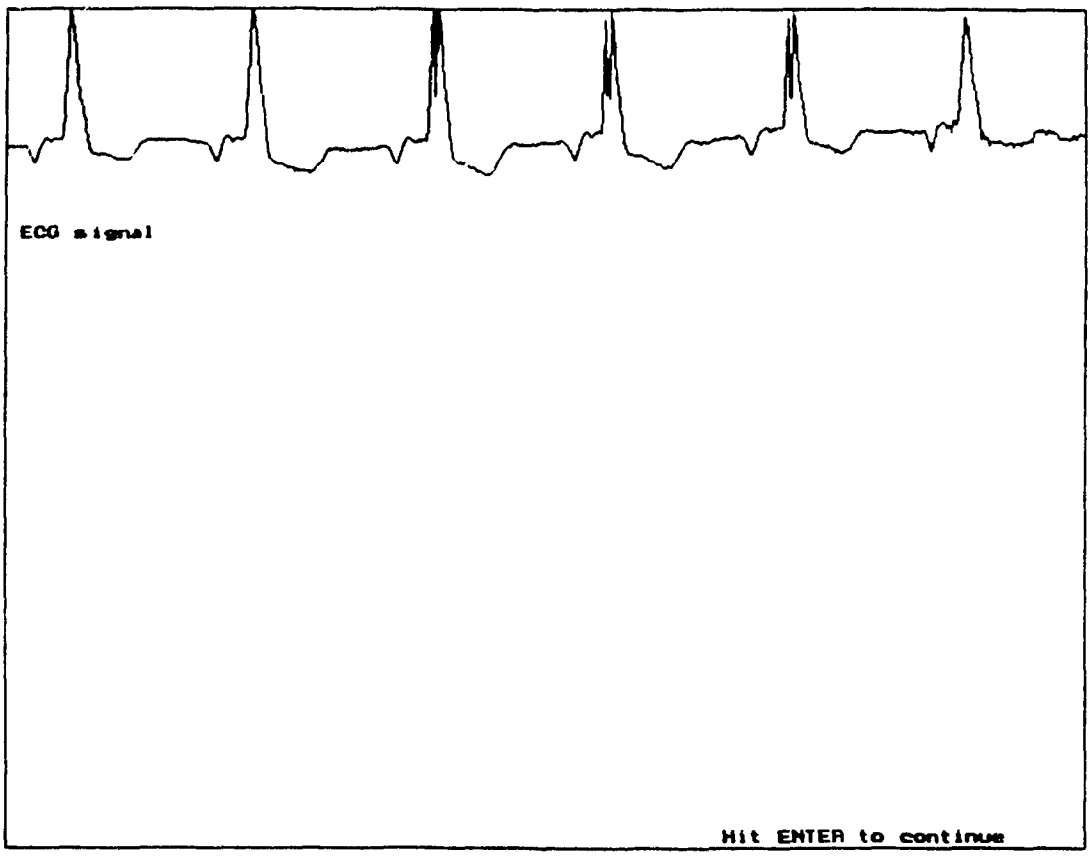


Fig. 5.2 - Example of ECG signal with every second point graphed.

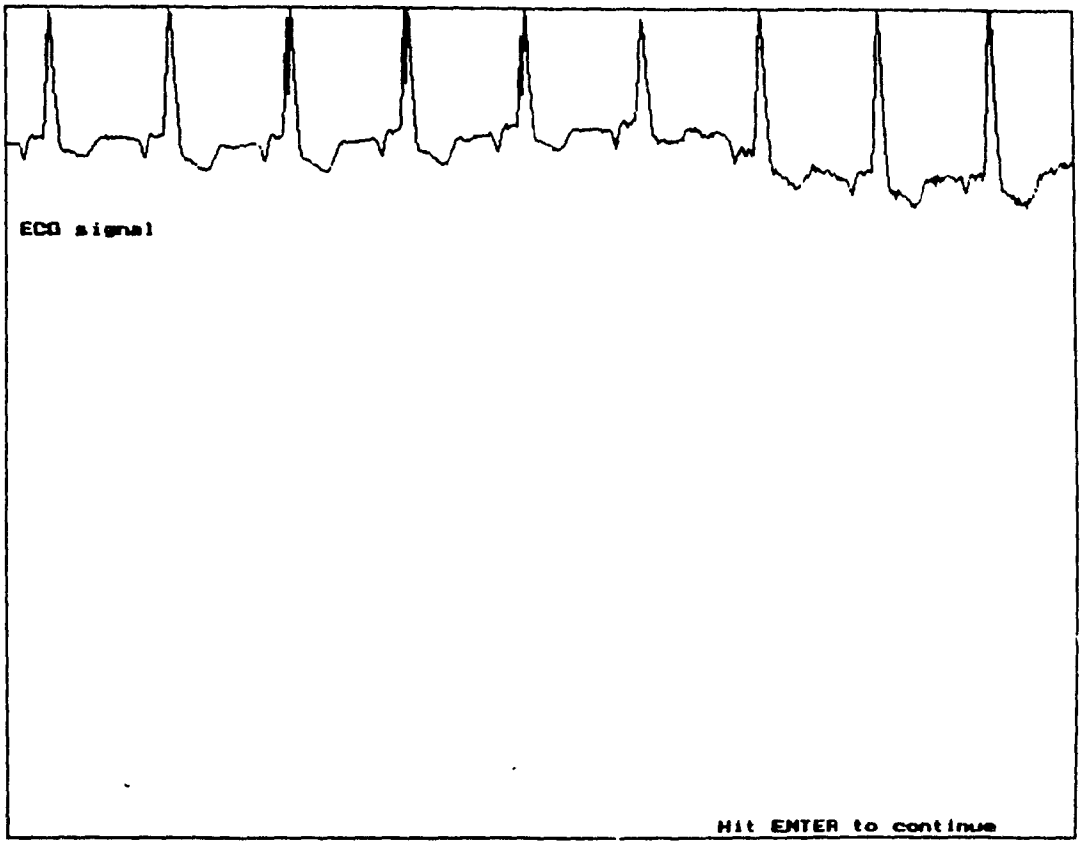


Fig. 5.3 - Example of ECG signal with every third point graphed.

5.2 - WINDOWING.

A second feature is the windowing capability of this system. This allows the user to window right or left, keeping a chosen percentage of the current information on the screen. Three examples are shown to illustrate this feature. The first set of screens, figure 5.4, shows an example of windowing right, on a graph showing every point where 33% of the screen will be kept. Carrying over 33% corresponds approximately to carrying over one R-R interval. A single R-R interval corresponds to about 200 points. When windowing right, the last R-R interval in the current screen will be the first R-R interval on the next screen. When windowing left, the first R-R interval on the current screen will be the last R-R interval on the next screen. Figure 5.5 shows an example of windowing left with 50% of the screen carried over, in a case where every second point is graphed. Therefore the first three of the current six R-R intervals will be the last three of the next screen. The third set of screens, figure 5.69, shows an example of windowing right again but with an ECG signal and its second difference, with every third point graphed and 66% of the screen being kept from one screen to the next. Therefore the last six R-R intervals of the current screen correspond to the first six in the next screen. In figures 5.4 and 5.6 note how the last part of the first screen corresponds to the beginning of the second screen, and in figure 5.5, see how the

beginning of the first screen corresponds to the end of the next screen. The dotted line marks the portion of the screen carried over from the previous screen.

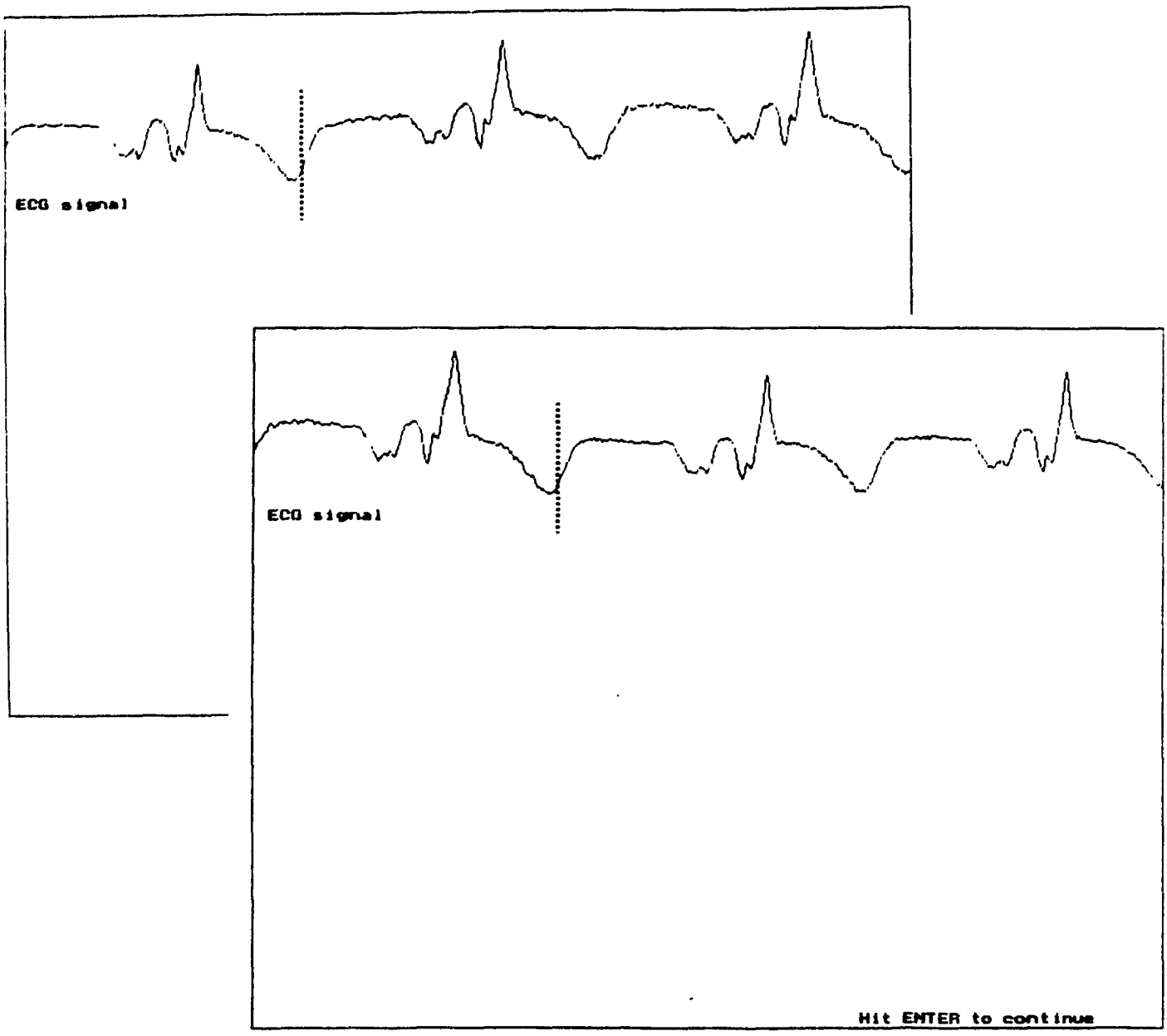


Fig. 5.4 - Windowing right, every point, ECG signal, 33% carry over.

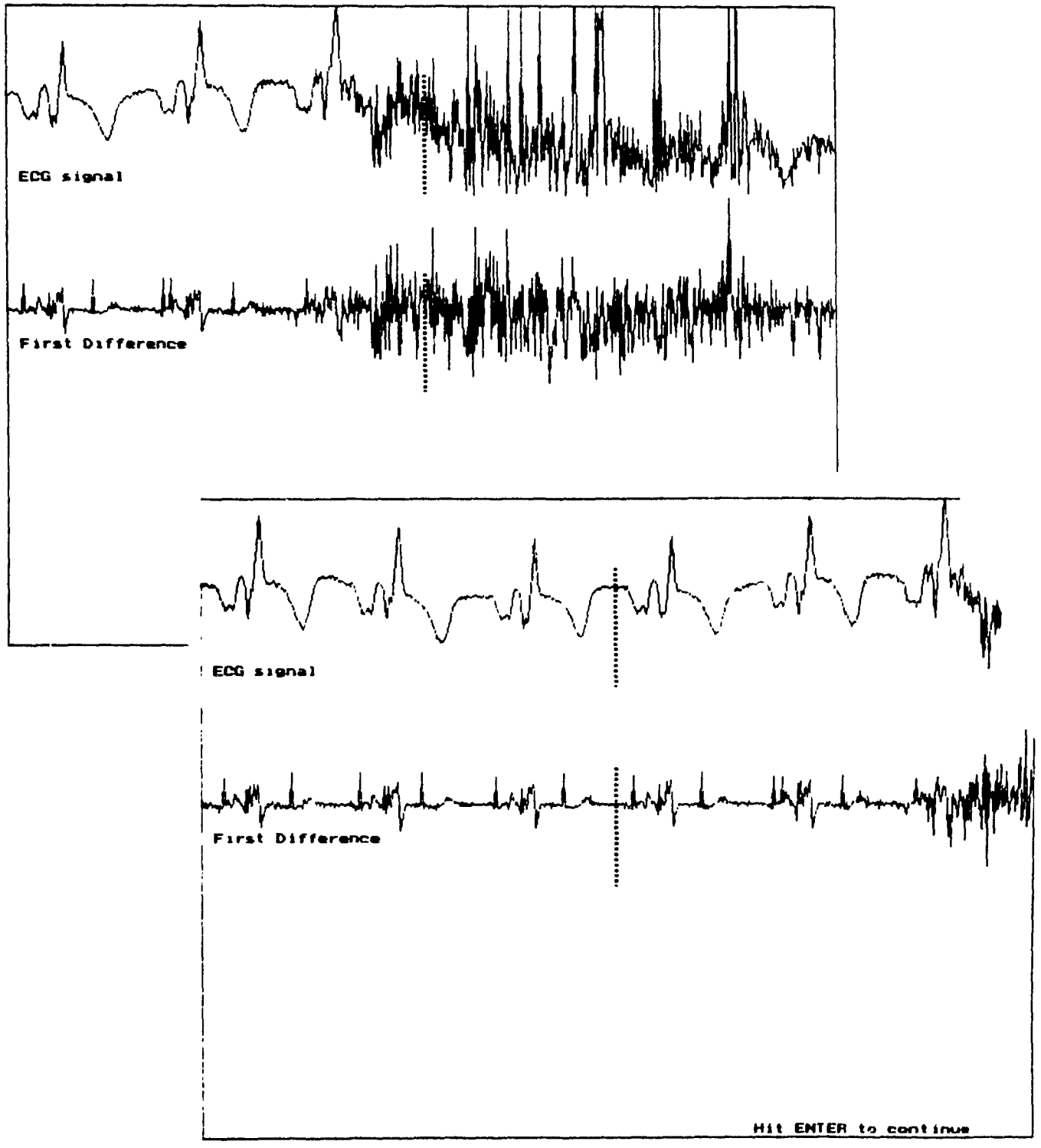


Fig. 5.5 - Windowing left, every second point, ECG signal and first difference, 50% carry over.

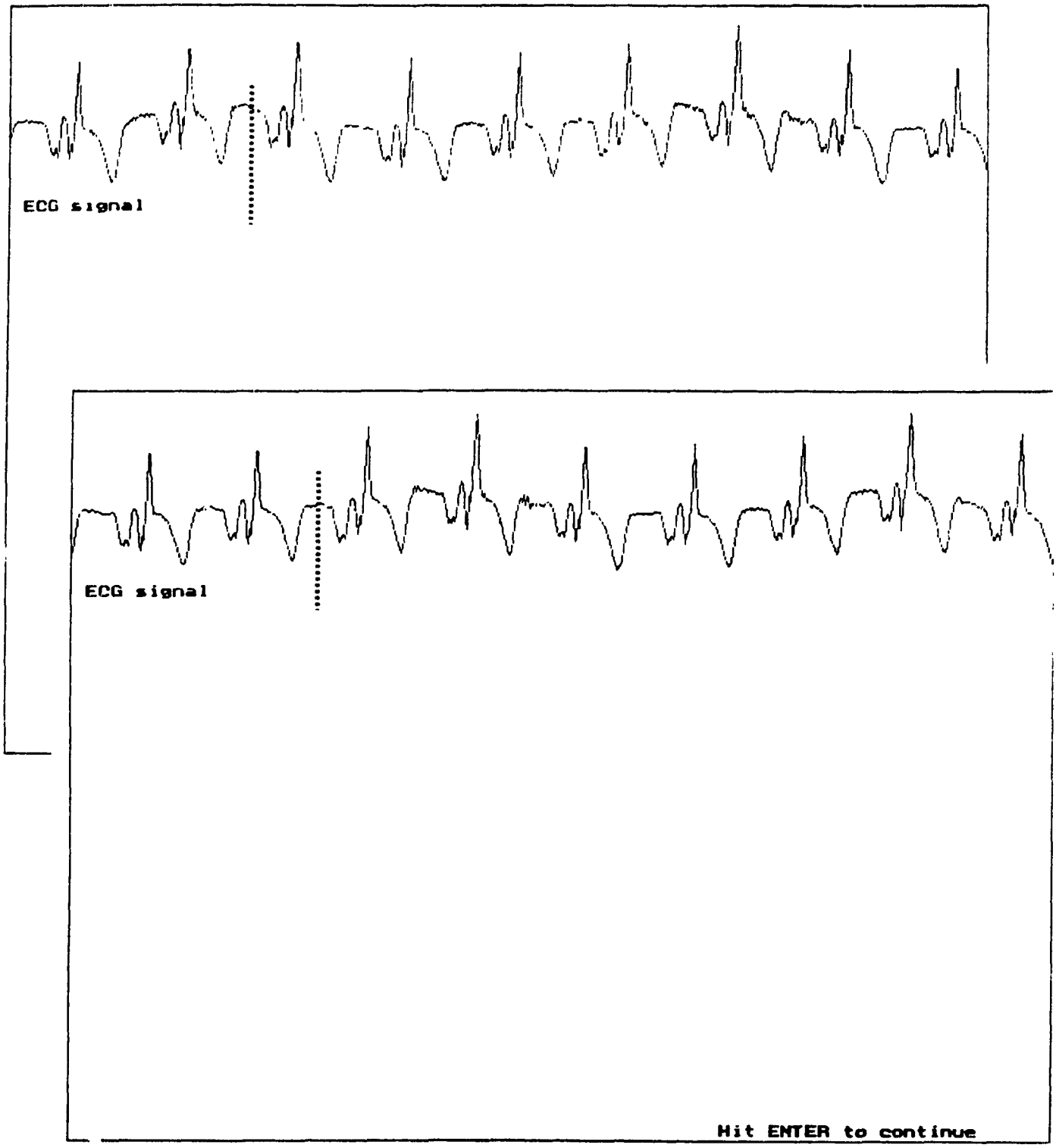


Fig. 5.6 - Windowing right, every third point, ECG signal 25% carry over.

5.3 - BEAT DETECTION.

A third feature is the beat detection capability of the system. It is one of the options in the transformations menu. The beat detection is based on the second difference. It looks for the largest negative slope within a certain range, and marks it as the onset or end of a QRS interval. To eliminate the detection of a same interval more than once, the process is turned off for a determined amount of time. This system is not an analysis system but a tool to assist in the analysis. The method used to detect a beat is not a smart one. It simply looks for negatives slopes within a certain range. It is thus up to the user or "analyst" to interpret the results or beats detected. The way a beat is marked is with a "B" at the point where the slope fits the criteria. The rest of the points are marked by a line. Four examples illustrate this feature. Figure 5.7 shows an ECG signal with every point graphed with the beat detection option. Figure 5.8 illustrates the beat detection with every second point graphed and finally figure 5.9 with every third point graphed. Figure 5.8 also shows the second difference which is used to detect the beats. This will allow you to note which points or slopes are used to detect the onset of a QRS interval. Figure 5.10 shows a case where artifact affects the beat detection algorithm. As mentioned earlier, once a beat has been detected, the procedure is turned off for 1/5th of a second or 50 points to prevent the detection of a same beat. When noise interferes, the results are unpredictable. Figure 5.10 is a classic case of this. We

see that the noise causes many slopes to erroneously satisfy the selection criteria of the onset of a new beat. Every 50 points is marked as a new beat. At this point it is up to the user to conclude that noise is interfering with the original ECG signal.

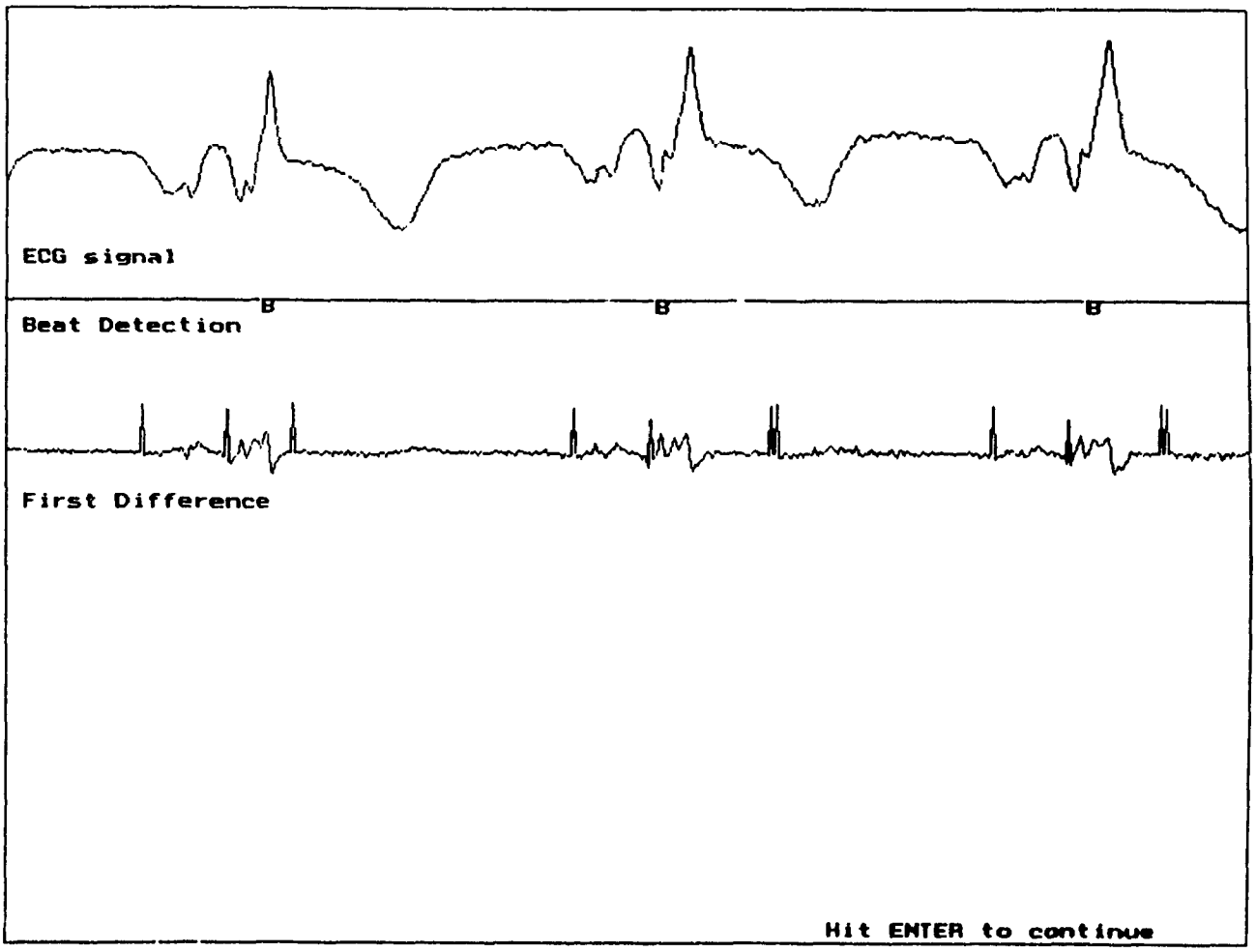


Fig. 5.7 - Beat Detection with every points of the ECG signal graphed.

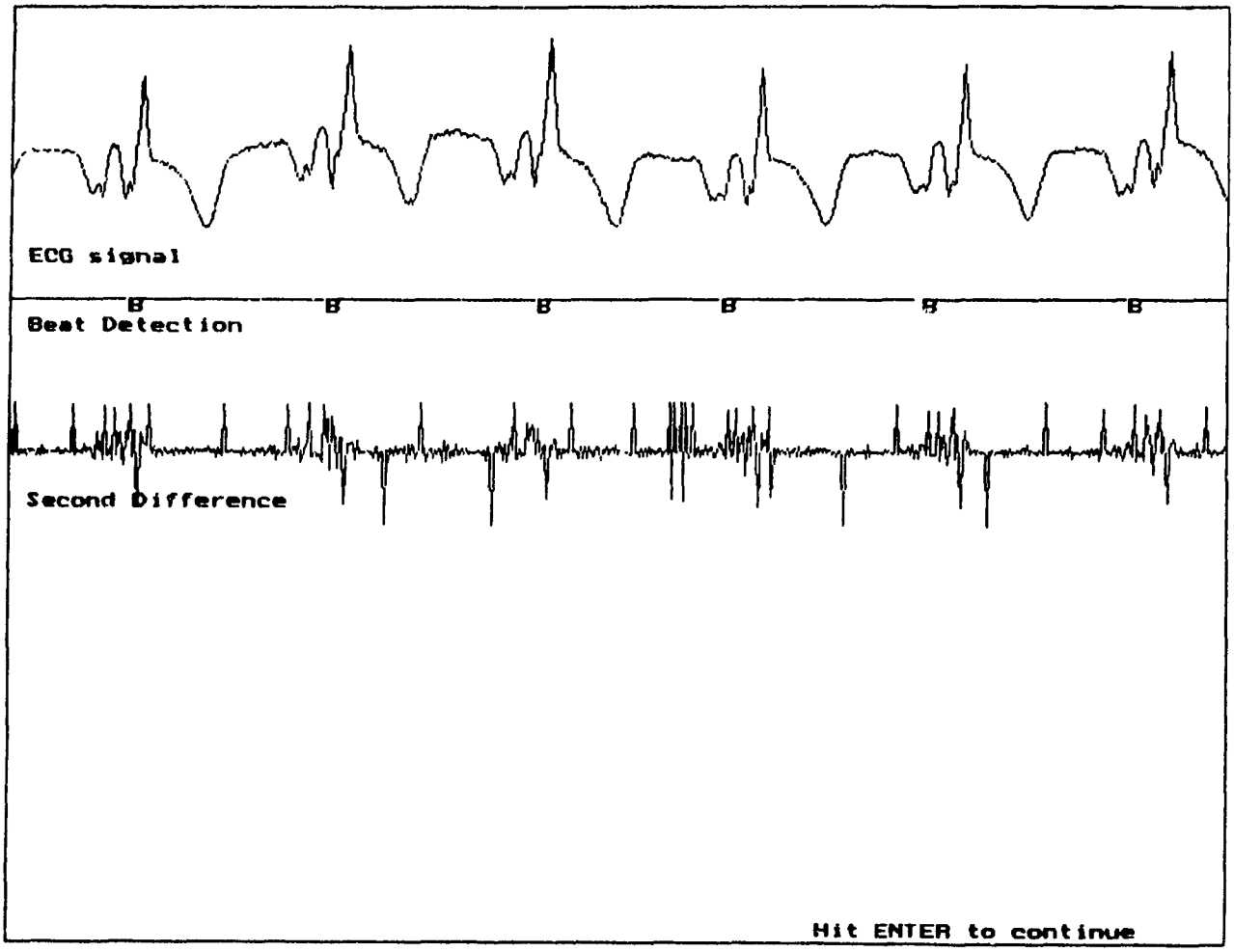


Fig. 5.8 - Beat Detection with every second point of the ECG signal graphed.

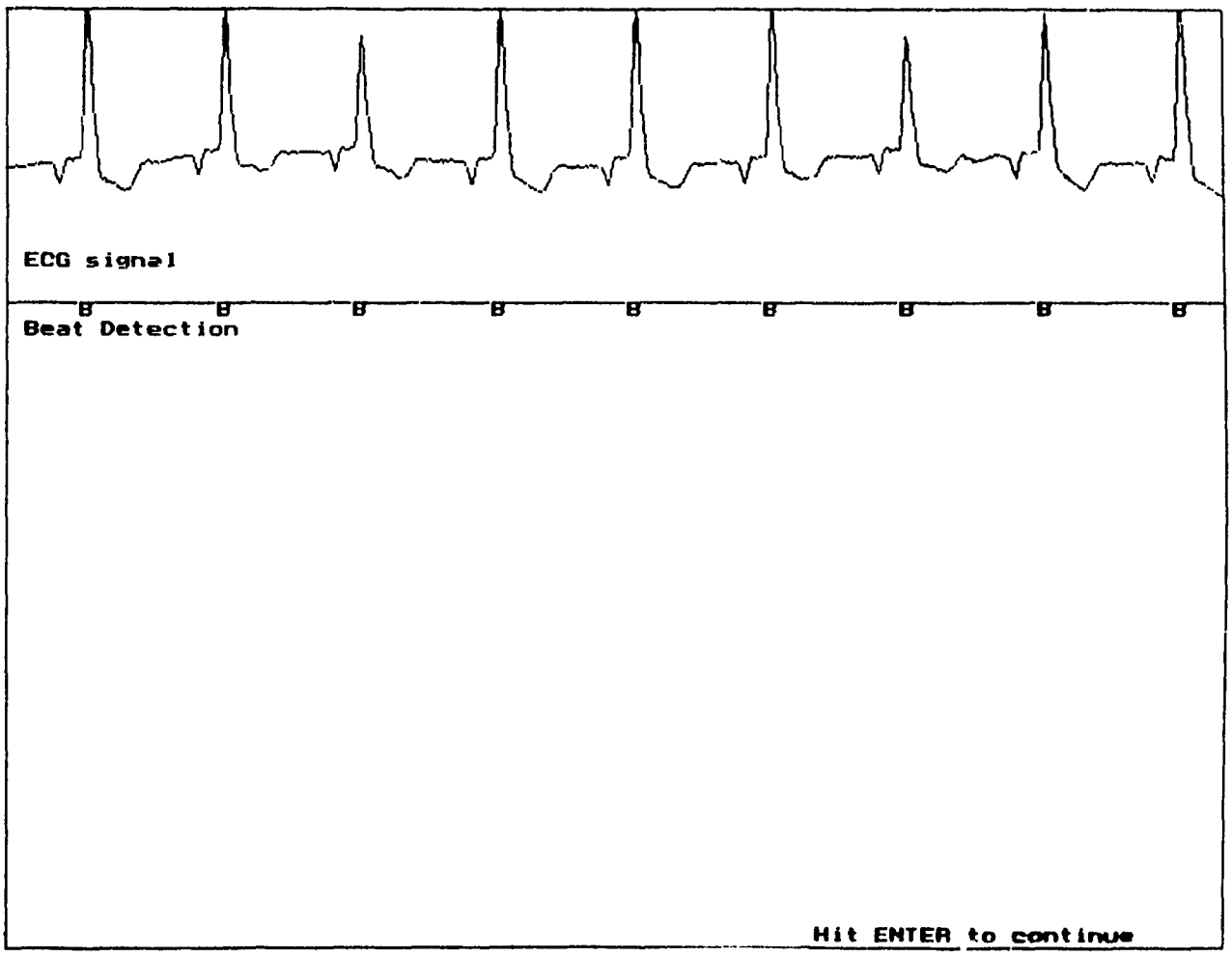


Fig. 5.9 - Beat Detection with every third point of the ECG signal graphed.

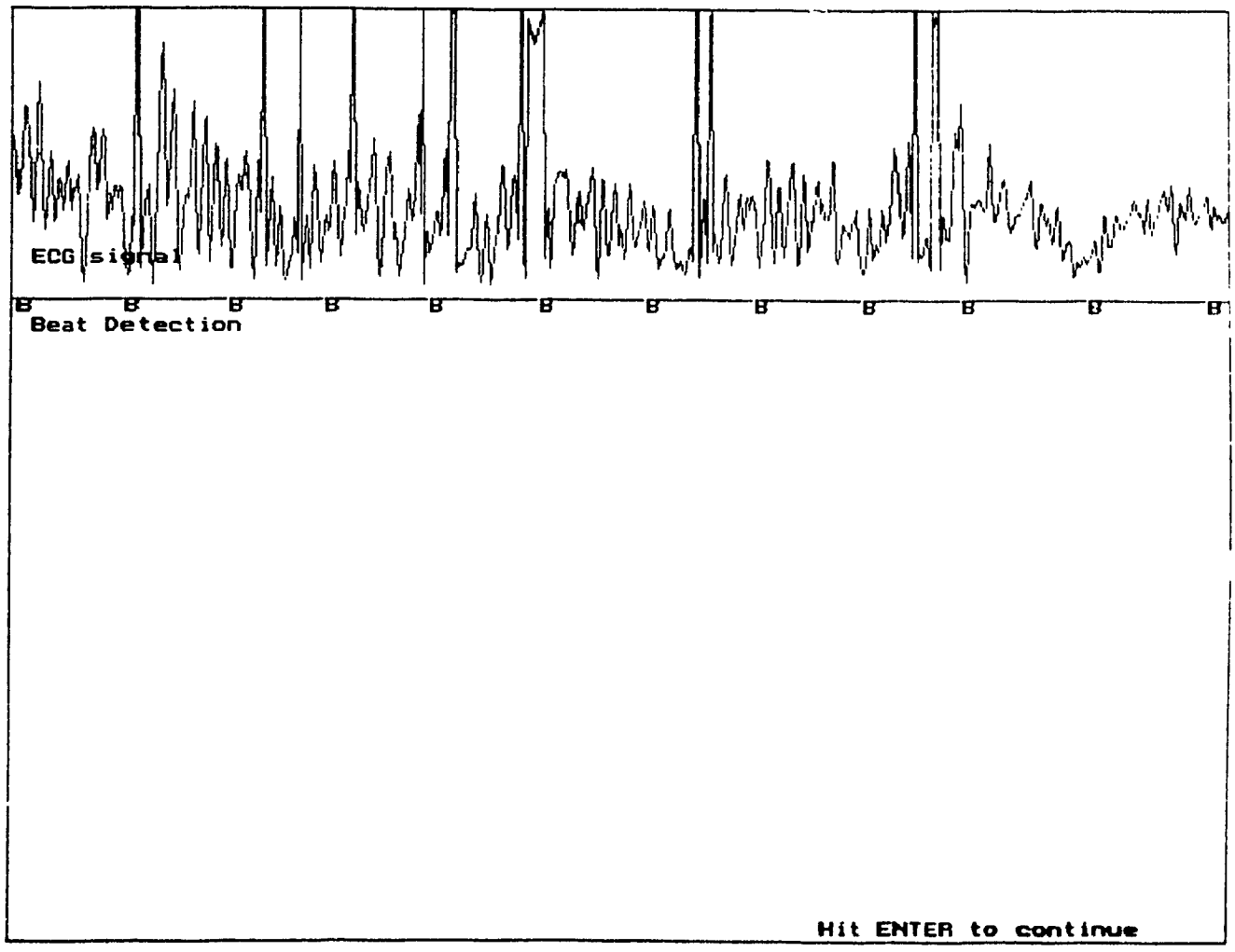


Fig. 5.10 - Beat Detection with the interference of noise.

5.4 - SPECTRAL ANALYSIS.

A fourth feature is the spectral analysis of an extracted segments. As discussed in section 3.4 the power spectrum is a powerful tool in detecting certain arrhythmias. Figures 5.11 and 5.12 will illustrate a baseline shift. Remember that baseline shifts are characterized by a predominance of frequencies below 2 Hz. Figure 5.12 shows this well. Figures 5.13 and 5.14 are an example of high frequency artifact within the ECG signal. Figure 5.13 shows the extracted segemnt and figure 5.14 is the corresponding power spectrum. Figures 5.15 though to 5.18 are illustrations of the power spectra of two different shaped QRS waveforms.

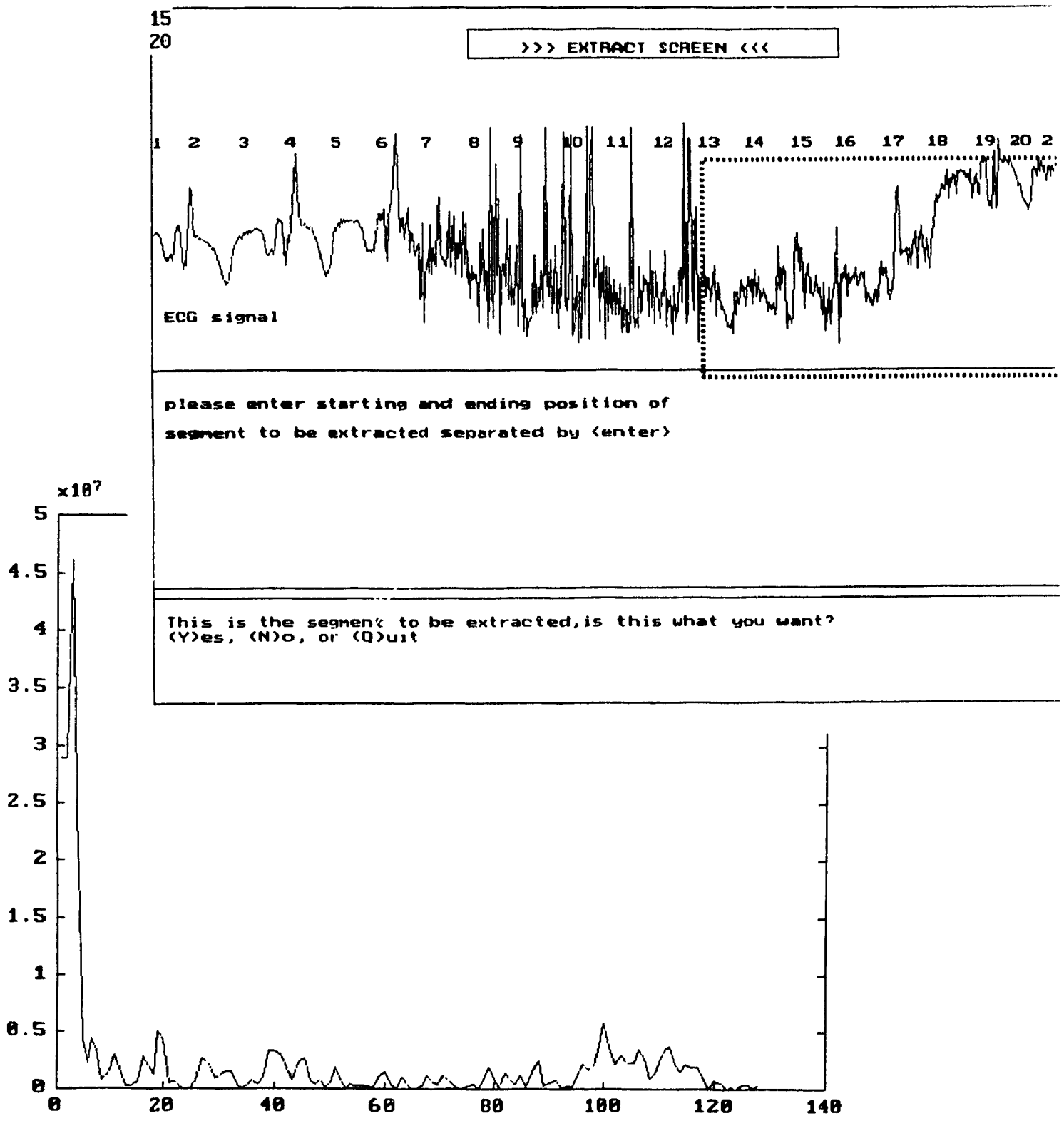


Fig. 5.11 - Power spectrum of an extracted segment showing a shift in the baseline.

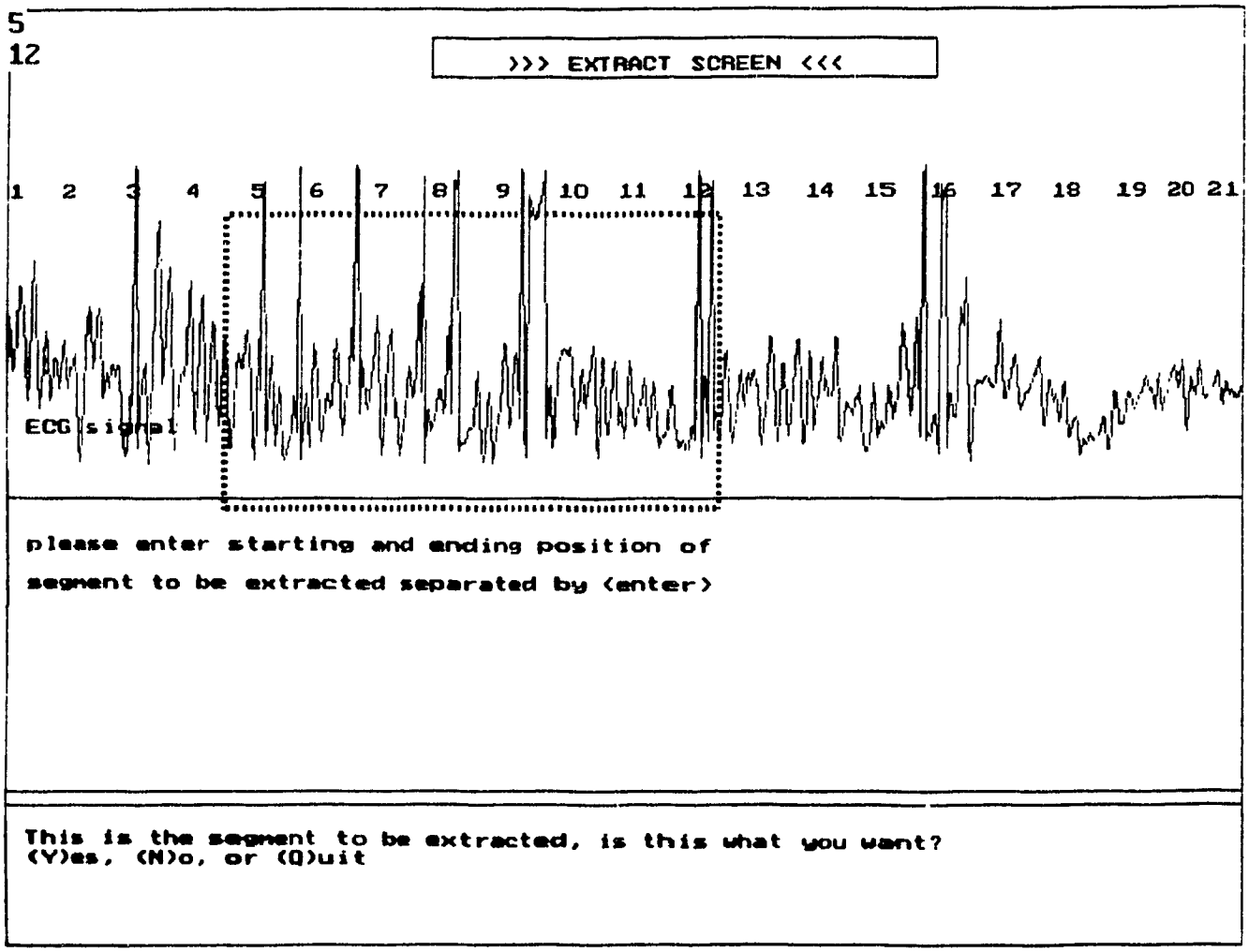


Fig. 5.12 - Extracted segment of an ECG signal with high frequency artifact.

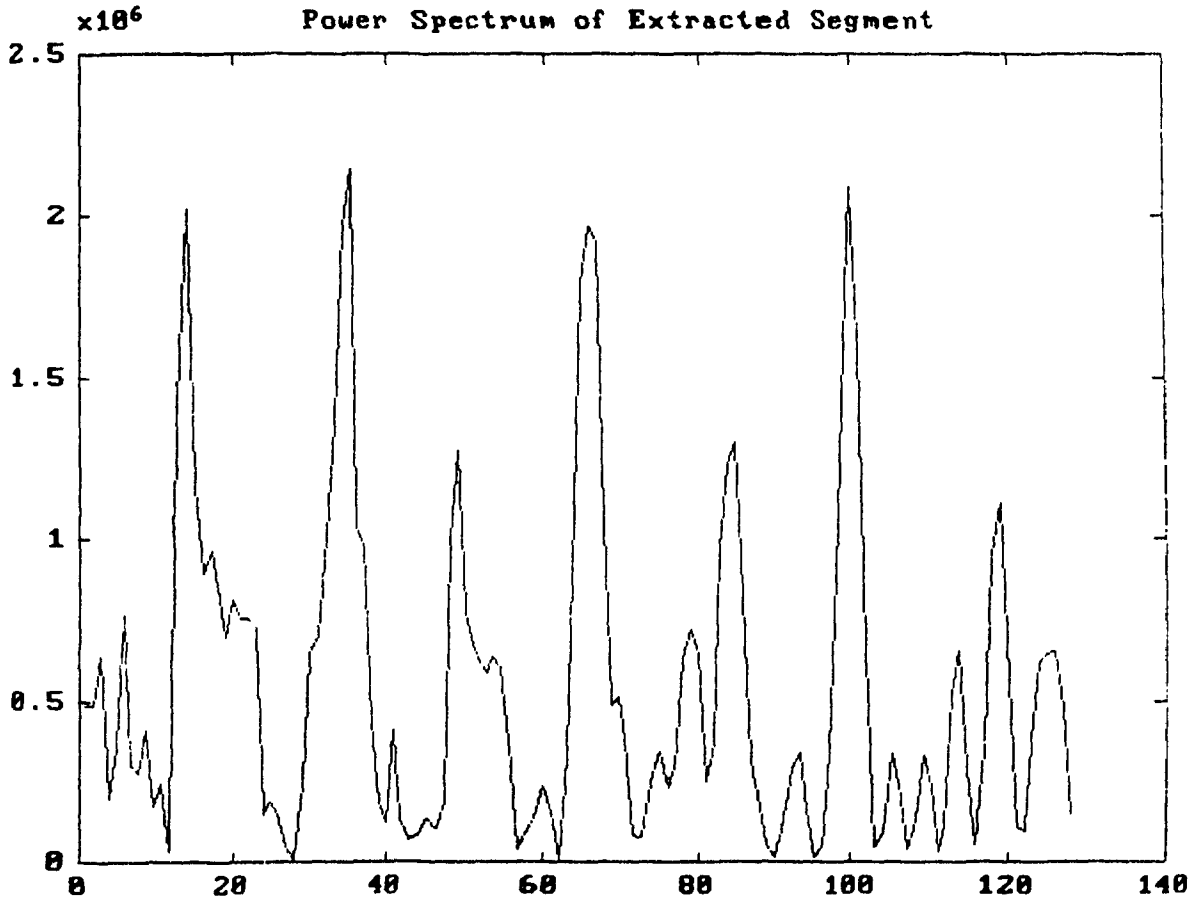


Fig. 5.13 – Power spectrum of an extracted segment showing high frequency artifact.

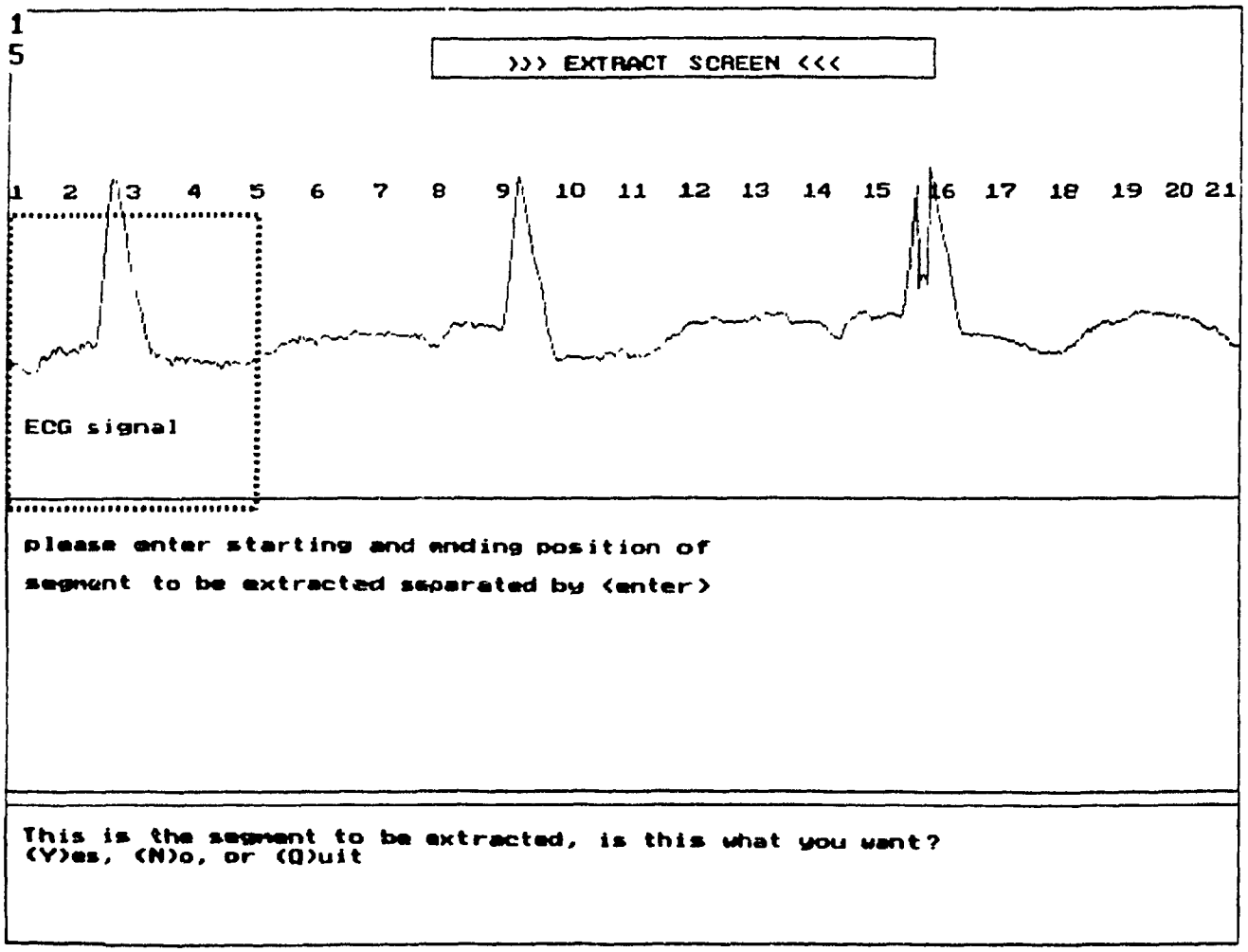


Fig. 5.14 - Extract screen of a first shape of a QRS interval.

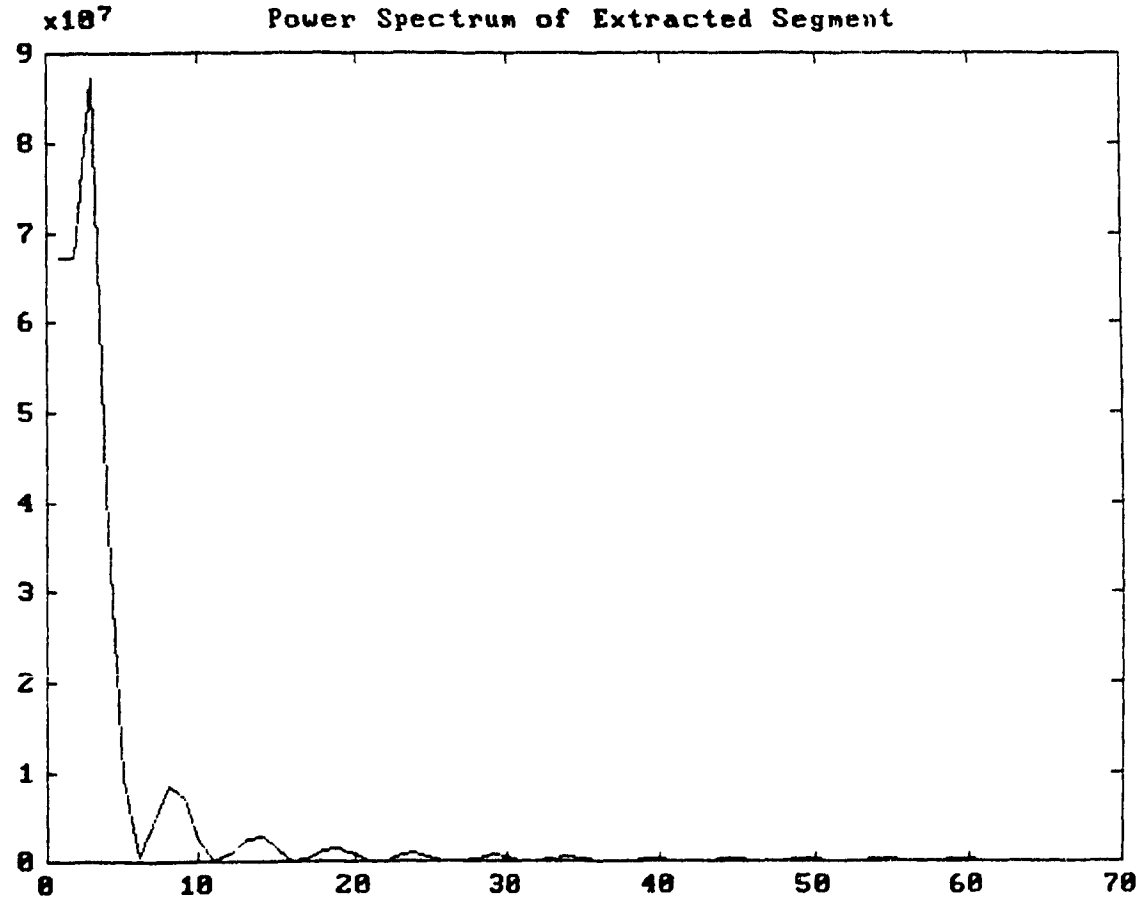


Fig. 5.15 - Power spectrum of QRS waveform in figure 5.14.

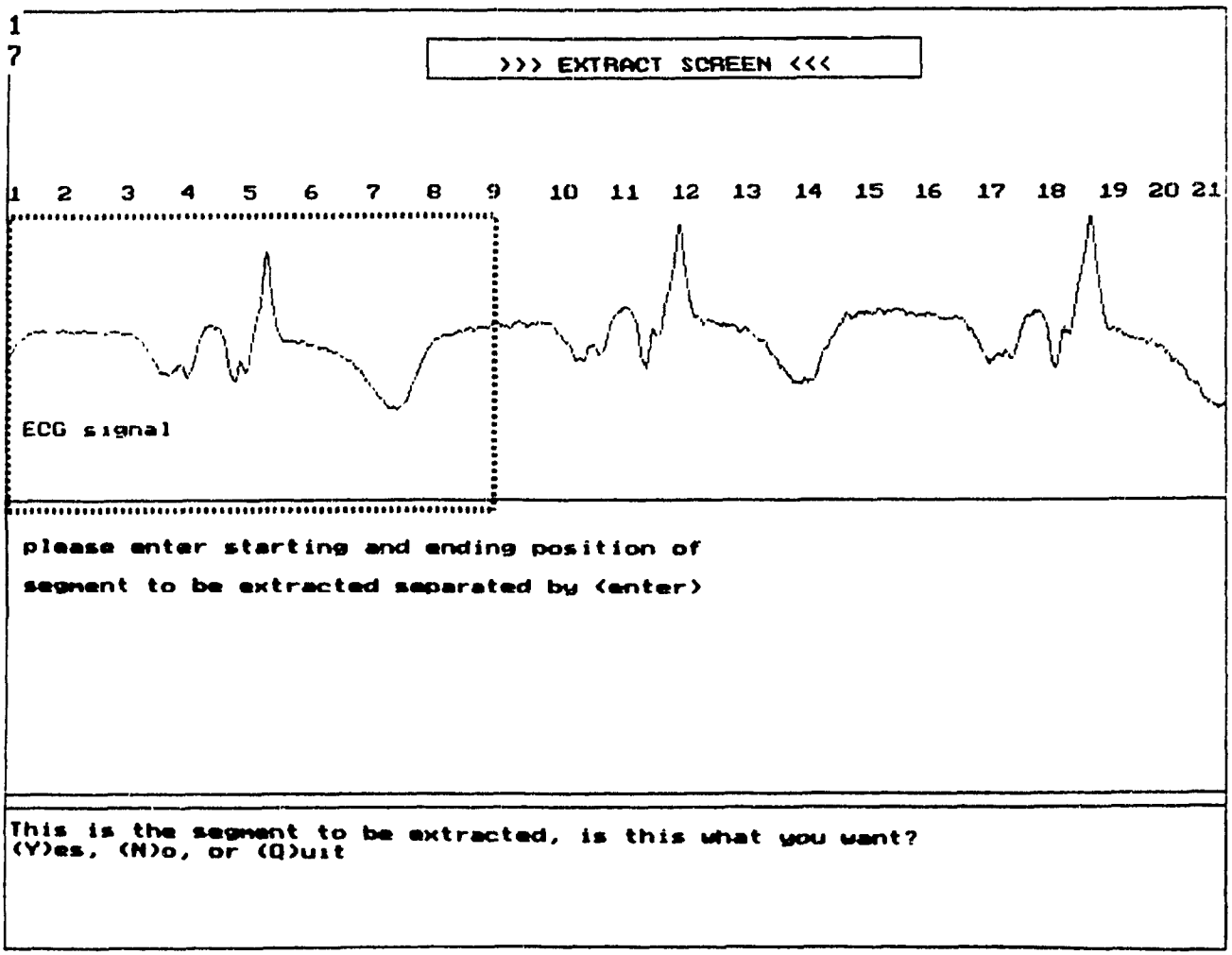


Fig. 5.16 - Extract screen of a second shape of a QRS waveform.

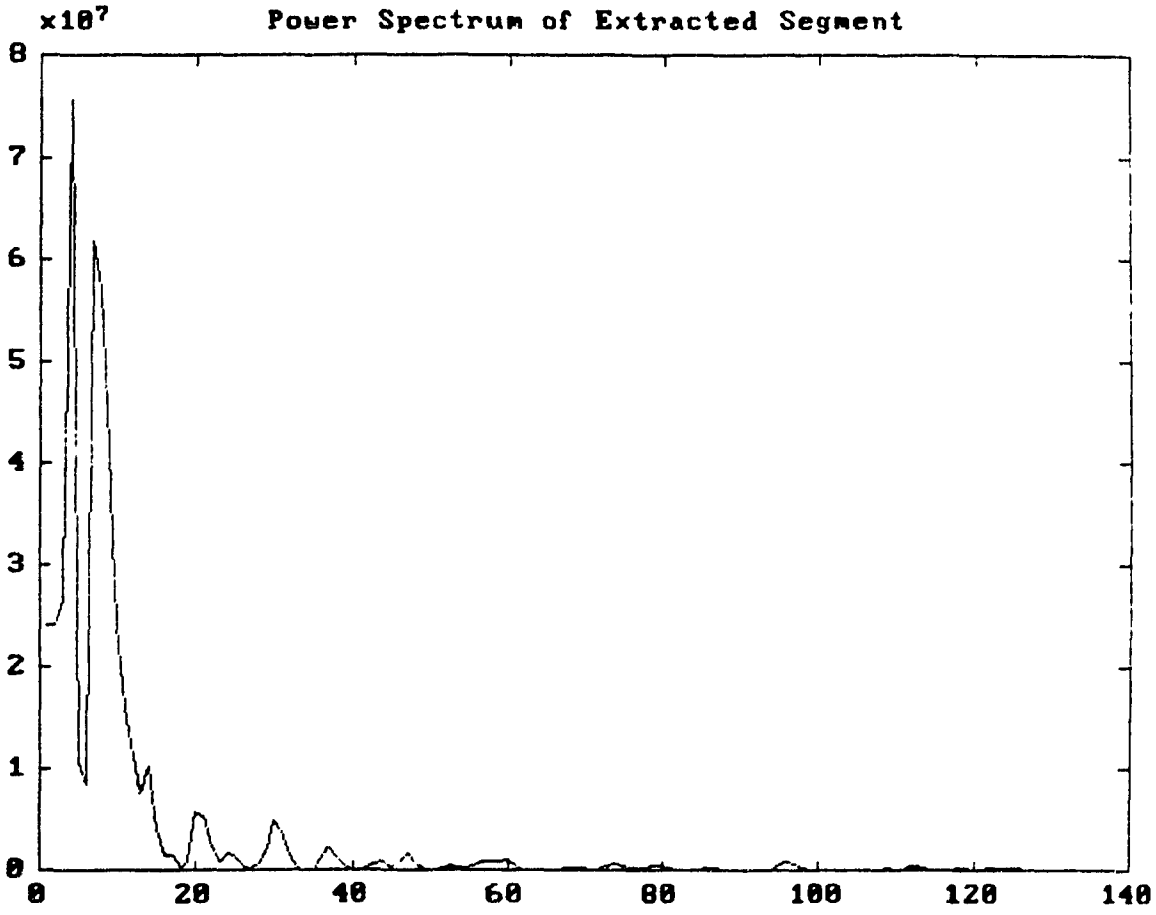


Fig. 5.17 - Power spectrum of QRS waveform in figure 5.16.

5.5 - SIGNAL FILTERING.

The last demonstration is of the filtering capabilities of the system. We use the filtering algorithm available in MATLAB which is explained in section 3.4. The purpose of the filtering algorithm is to reduce or eliminate unwanted signals, such as those due to noise. The following examples will illustrate the results using various parameters. To demonstrate the effects of the filtering, the same screen of signals is used with different values for the filtering vectors *a* and *b*. Remember the equation is the following:

$$y(n) = b(1)*x(n) + b(2)*x(n-1) + \ldots\ldots + b(nb+1)*x(n-nb)$$
$$- a(2)*y(n-1) - \ldots\ldots - a(na+1)*y(n-na)$$

Figures 5.18 through to 5.21 all have the original ECG signal, which is the same in all four examples, and the result of the filtering with varying values of a and b.

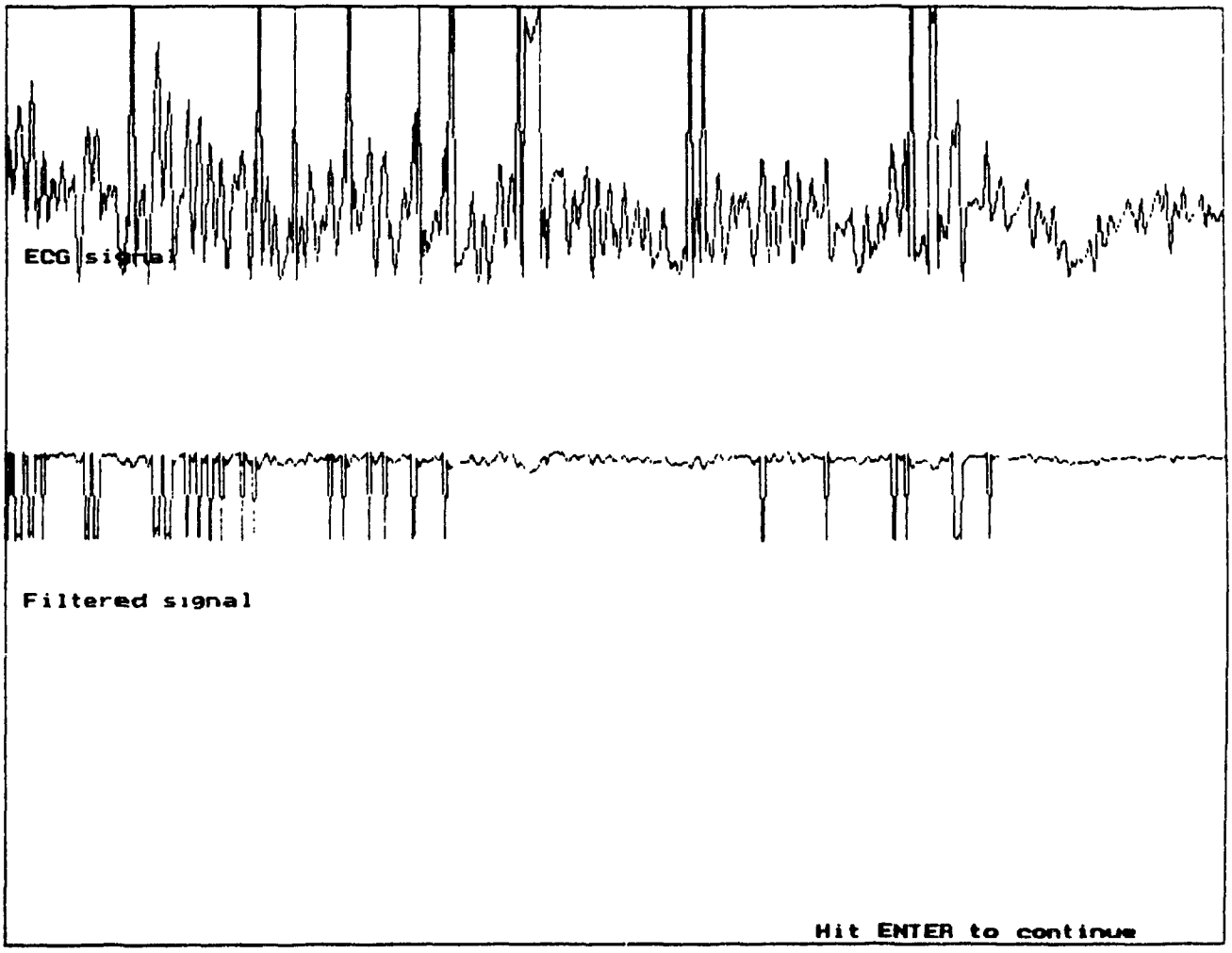


Fig. 5.18 - Result of filtering where a = 0.90 and b = 0.10.

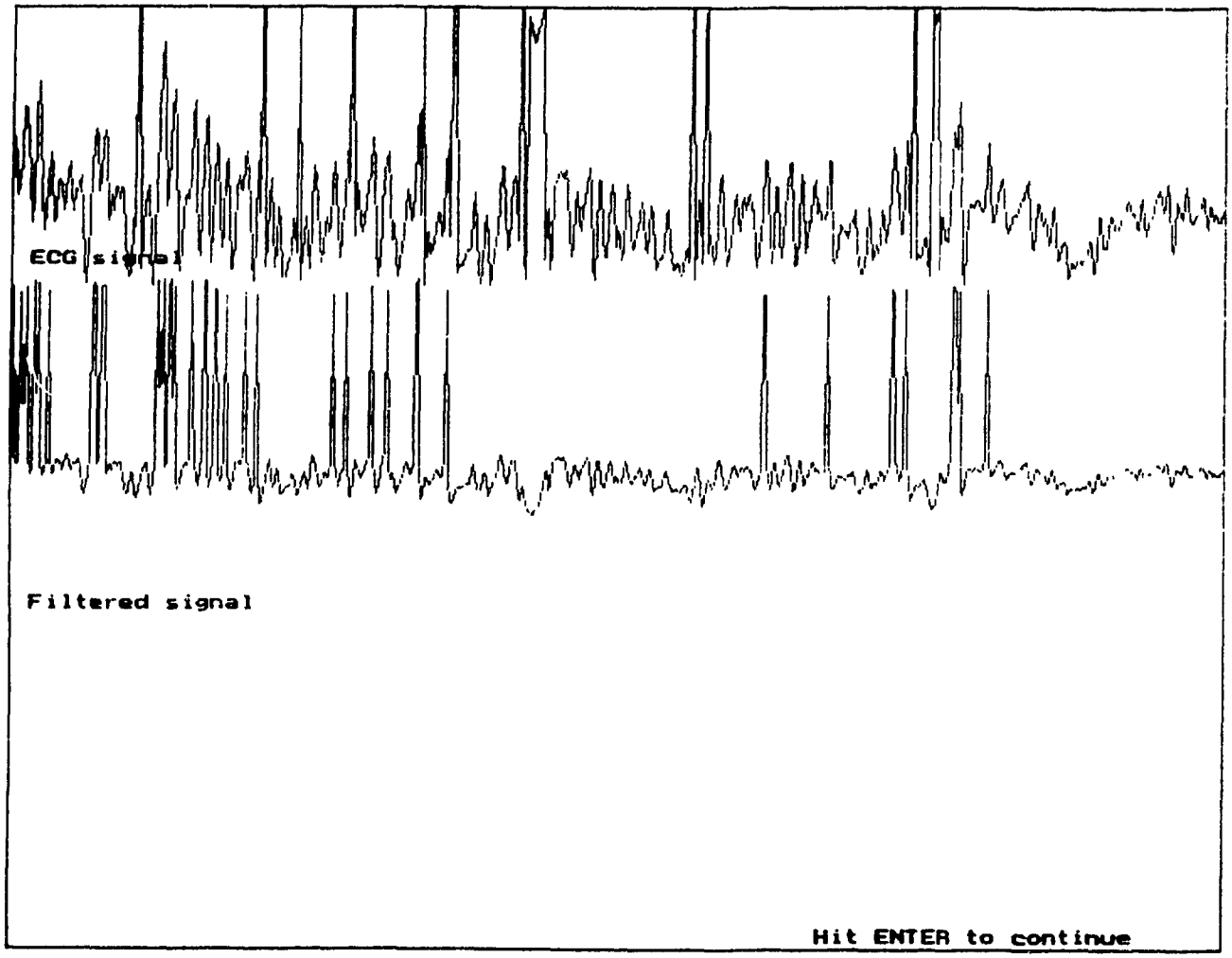


Fig. 5.19 - Result of filtering where a = 0.75 and b = 0.25.

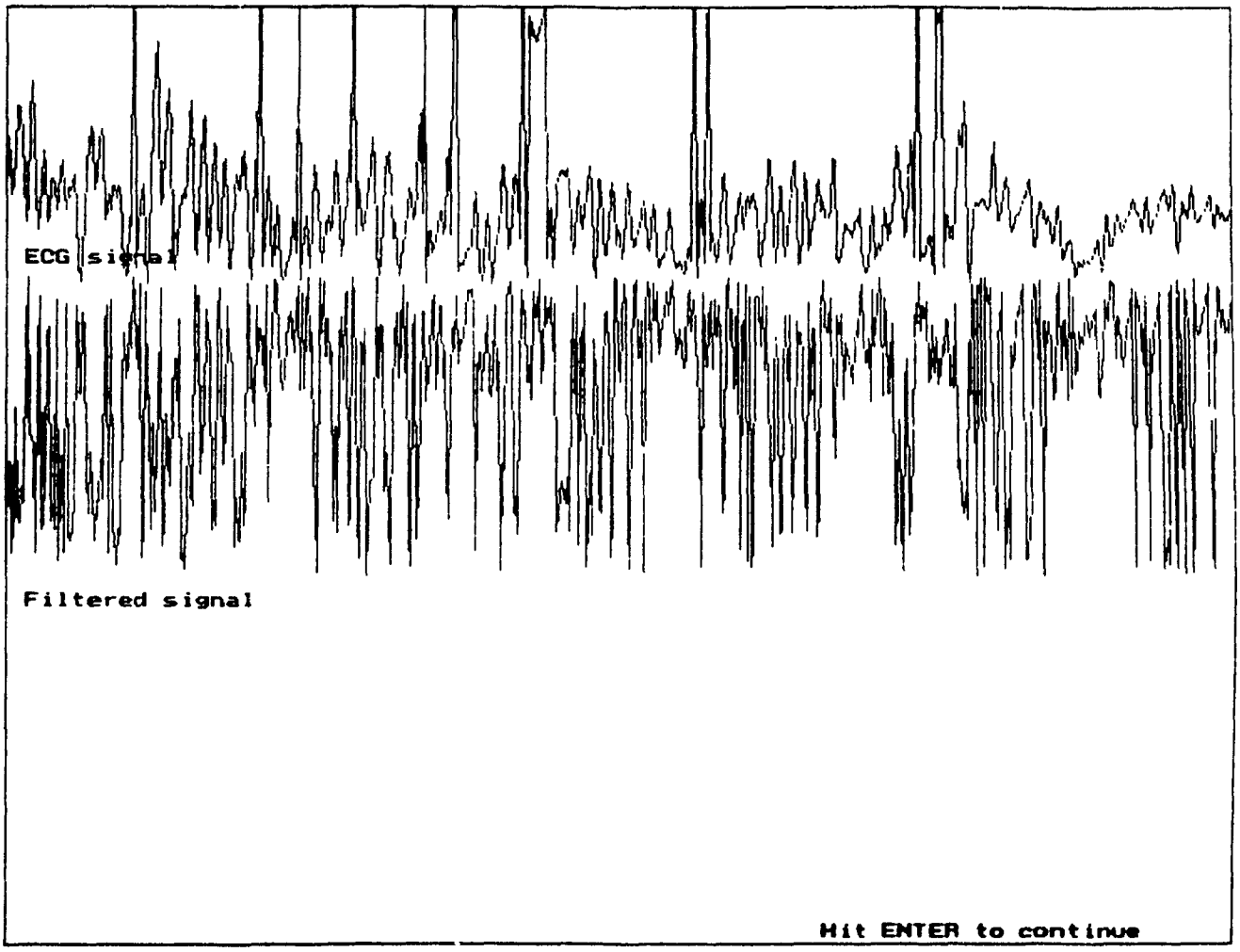


Fig. 5.20 - Result of filtering where a = 0.25 and b = 0.75.

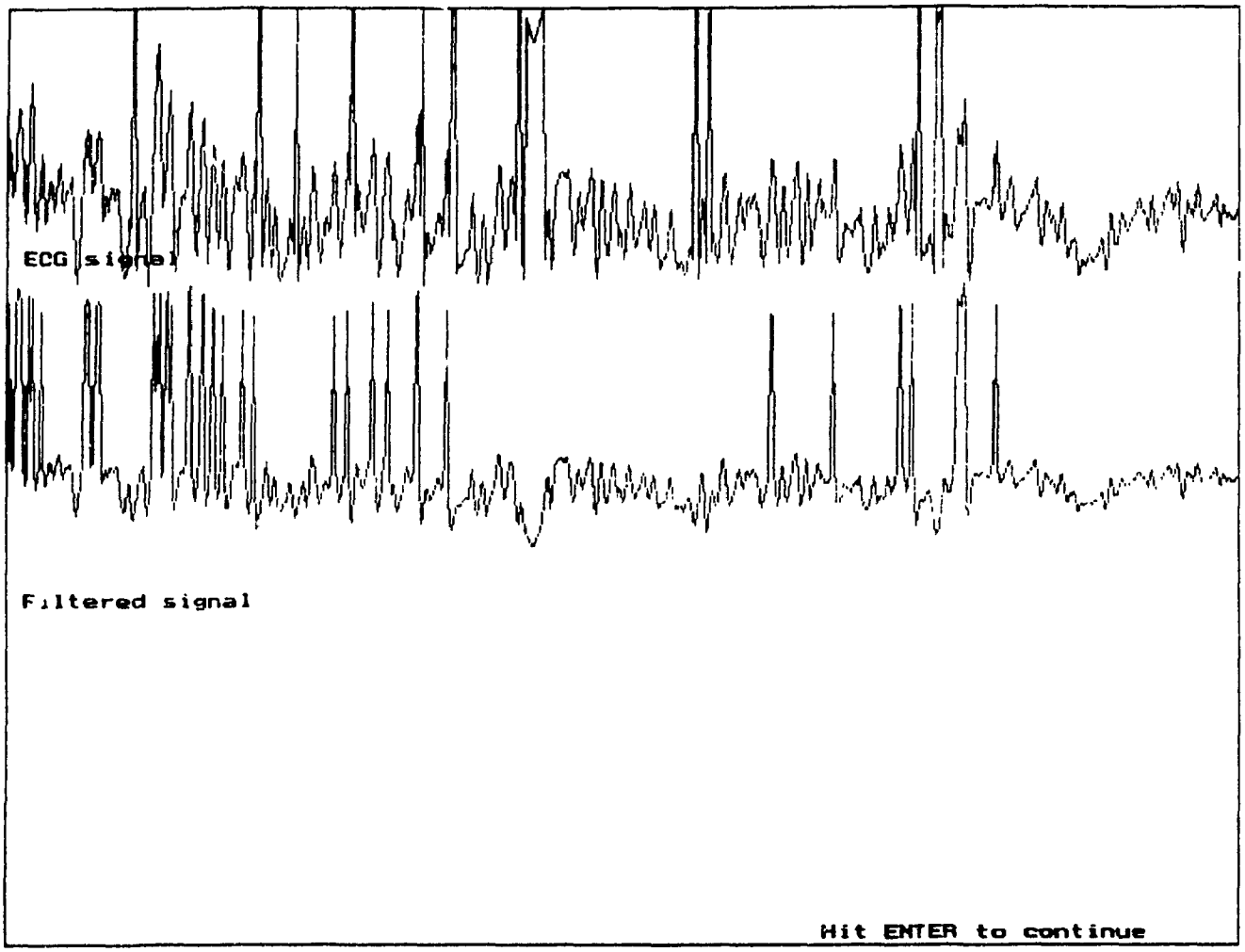


Fig. 5.21 - Result of filtering where a = 0.66 and b = 0.34.

This completes the demonstration of the features of the software developed. The possibilities are limited only by the imagination and needs of the user.

Chapter VI
CONCLUSION

This system was designed as a prototype and not a commercial product. The idea was to construct the skeleton of a system that would serve as a tool in the analysis of ECGs. This was accomplished. Furthermore, the implementation of the system was done in a way which would facilitate the addition of any new function as required for analysis. Through MATLAB the user can create his own transformations by adding more options to the transformation menu and including these choices in the corresponding MATLAB script. Since MATLAB offers many signal processing functions, this is a trivial task. A list of functions offered by MATLAB is included in appendix A. The system in its present state is functional and simple to use.

Should the system be refined for commercial use, I would recommend the following enhancements. First, it would be desirable to add a certain degree of analysis capabilities to the beat detection routine: the program could indicate when an irregular beat has been detected and even maybe indicate which type of anomaly has been found. A second modification would be to add color to the displays. For example each QRS interval could be a different color, as well as the corresponding transformations. This would delimit clearly one beat from the next. A third modification would be to the selection portion of the system. There

should be default values to each option which the user could select by simply hitting the enter key. Also, when the user has initiated the system once and decides to select new options, the system should show the last choices and ask the user which ones he wishes to modify. This would reduce the need of having to select all options each time.

These modifications would be enhancements to the system, without altering its mandate. It is very easy to get over ambitious and include many features, how ever it is important to remember the goal of this system. The features developed here form the basis of a low cost system. In its present format it provides a simple off-line tool for inspecting ECG signals.

APPENDIX A

LIST OF SOME FUNCTIONS AVAILABLE IN MATLAB.

Signal Processing Functions:

* abs: complex magnitude
* angle: phase angle
* conv: convolution
* corrcoef: correlation coefficients
* cov: covariance
* deconv: deconvolution
* fft: fast Fourier transform (FFT)
* ifft: inverse fast Fourier transform
* filter: digital filter
* fftfilt: overlap-add method of filtering using FFT
* spectrum: power spectrum estimate of one or two data sequences

Columnwise Data Analysis Functions:

* max, min: maximum and minimum value
* median: median value
* std: standard deviation
* mean: mean value
* corrcoef: correlation coefficients
* diff: difference function, approximate derivative
  n-th difference function

Various matrix manipulation functions

Various polynomial manipulation functions

Graphing Functions:

* plot: linear X-Y plot.
* mesh: 3-dimensional mesh surface
* contour plot
* title: plot title
* xlabel: x-axis label
* ylabel: y-axis label

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