Development of Electrocardiographic Image Processing Software

by

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Submitted to the Department of Electrical Engineering

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Abstract

An electrocardiographic image processing software system was developed for a Microsoft Windows PC environment. The purpose of this project was to develop a low-cost system to perform all the necessary functions regarding electrocardiographic body surface mapping. Electrocardiography is the measuring of electrical potentials on the thorax to gain insights into the electrical activity taking place within the heart. This information can be used to diagnose many cardiac diseases or abnormalities. The developed system allows the user to display electrocardiographic data in the time and space domains under a variety of parameters. The system also performs a number of temporal and spatial functions to analyze the data. The field of body surface mapping is relatively new. The vast majority of the work in this field is taking place in an experimental setting. The technique is presently not exercised on a wide scale in clinical cardiology. A number of significant advancements are presently occuring in the field of body surface mapping. Many of these advancements which will make clinical applications more feasible are incorporated into this system. The development of electrocardiographic image processing software on low-cost user-friendly desktop computers will play a role in making body surface mapping a more practical and affordable technique for clinical applications.

Thesis Supervisor: Richard Cohen
Title: Professor of Health Sciences and Technology

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Finally and most importantly, I would like to thank my parents whom I greatly admire for supporting and inspiring me in all my educational and personal pursuits.

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Chapter 1

Electrocardiography

1.1 History of Electrocardiography

The study of electrocardiography began in 1856 when Kolliker and Muller[1] became the first to attempt to measure on the body surface the electrical potentials generated by the heart. Since that time the field of electrocardiography has undergone many changes in both theory and tactics. Researchers have used a variety of tools and models to gain insight into electrocardiac activity. This has led to a number of breakthroughs in experimental and clinical cardiology.

The early studies by Kolliker, Muller and others were done by recording the potential differences of pairs of electrodes placed on the body surface in a variety of positions. Every study performed in this era used a different criteria for the placement of

these electrocardiographic leads. Einthoven[2] was the first to utilize methods which have become present day standards when he performed tests with three lead pairs placed in the shape of a triangle with points at the right arm, left arm, and left leg. In 1932 Wolferth and Wolfe[3] performed studies with electrodes placed at the back and apex. This method was found to be very successful in the diagnosis of myocardial infarction, a common cardiac disease. After this event a variety of other methods were created with each author claiming a diagnostic advantage for his method over others.

In 1938 a joint committee was formed by the American Heart Association and the Cardiac Society of Great Britain and Ireland[4]. Their goal was to develop an international standard for a system of electrode placement to better facilitate communication in experimental and clinical cardiology. At the conclusion of the conference the group agreed on a twelve lead system of recording electrical activity. This technique became known as the ECG and is still presently in use (with minor modifications) as a clinical tool.

One shortcoming of the ECG is its inability to reflect the spatial features of electrical cardiac activity. Between the 1920's and 1950's researchers attempted to record cardiac potential as a three-dimensional time varying vector. This method is referred to as vectorcardiography. The results of this process is a vectorcardiogram, or VCG. In this era the assumption was made that the source of electrical cardiac activity could be modeled as a single dipole inside the heart. This dipole, it was believed, remained at a constant point and simply underwent changes in magnitude and direction. Researchers modeled this dipole as being located in a large homogenous conducting medium. Since the precise shape of this conducting medium was unknown, a variety of different coordinate systems were used to define this vector. Among the earliest were the cube, the trihedron, and the tetrahedron each of which attempted to establish orthogonal or rectilinear systems of recording electrical signals based on the structure of the torso.

In 1946 to correct inconsistencies with this model and test data Burger and van Milaan[5] introduced the concept of the lead vector or correction coefficient. The potential measured at a point on the body surface, they claimed, was the dot product of the heart vector and the lead vector. This and other factors led to the necessity of huge amounts of mathematical analysis involved in the normalization, orthogonalization, and display of spatial vectorcardiographic data. Biological difference in every individual human and animal subject added to the complexity. The process of determining and displaying this data became very tedious. Schmitt[6] was the first to develop an electronic means of displaying the data by projecting the image of the cardiac vector on to a cathode-ray tube. This means of analyzing data became a beneficial tool in the clinical study of VCGs.

Due to variety of methods and theories used to derive VCGs, a standard system was not developed to obtain and interpret the data, unlike the ECG. Even though the VCG was technically more advanced than the ECG, the precision required in the electrode placement in addition to the lack of a standard system made it difficult for the vector method to become popular in clinical cardiology. While the vectorcardiograms continued to be used clinically they never replaced the ECG as the primary method for electrocardiographic diagnostics.

1.2 Body Surface Potential Mapping

A more intense method in observing electrocardiac activity is body surface potential mapping. The method began in 1910 when Kraus and Nicolai[7] produced diagrams to illustrate the spread of potential on the body surface. Their assertion that the potential distribution at the body surface corresponded to the potential underneath the skin

at the heart's surface was based on the principle of the distribution of electrical currents in volume conductors. In the mid 1910's Grodel and Koch[8] used electrocardiographic mapping to distinguish between the electrical activity in the right and left sides of the heart. They were able to produce the first isopotential maps for successive instants of the QRS complex. Keinle[9] was the first to record electrical activity intensely on the entire thorax for a single instant. His subjects were measured with almost 4000 electrodes placed in a grid with a spacing of about 1.5 cm. Samples were taken at intervals of 0.01 seconds.

All electrocardiac mapping up until the mid 1950's was done to support and clarify the single dipole theory. In 1956 Nelson[10] presented his initial studies to disprove this theory. Nelson recorded his potential measurements from electrodes situated closely together (2.5 cm apart) on a belt which was placed around the chest of a subject. With this data Nelson showed that at one given point in time multiple peaks and valleys occurred in the potential distribution around the chest. This demonstrated that more than a single dipole existed at a given instant. This discovery led Nelson and other researchers to develop a electrical model of a human heart which was more comprehensive that the single dipole theory. This discovery was followed by a decline of the VCG and an increase in the application of body surface potential mapping.

Since Nelson's time a number of studies utilizing potential mapping have been produced which have advanced the understanding of cardiac activity. Clinical cardiologist have also utilized BSPM to discover and diagnosis a variety of illnesses, including acute myocardial infarction, chronic myocardial, ischemia, chamber enlargements, ishemic heart disease, and pre-excitation syndrome.

New developments in other scientific fields have improved the effectiveness of body surface potential mapping. Advances in electrical engineering have allowed maps to be more comprehensive by providing for improvements in the accuracy and speed of electrical potential sampling and an increase in the number of electrodes which can be

simultaneously measured. Advances in computer science have given specialist the ability to interpolate and mathematically analyze test data more effectively.

Due to the tools of body surface potential mapping and other scientific advances, a more complete model of electrocardiac activity has been attained. The changes in the potential level on the body surface can now be accounted for by processes which take place during the depolarization and repolarization of myocardial cells[11]. During cardiac excitation, or depolarization, the transmembrane potential of a given cell becomes less negative in relation to its surrounding resting cells. A variety of physiologic and biophysical factors affect the resulting potential distribution on the body surface. These transmission factors can be observed in Table 1-1.

The solving of the relationship between the electrical activity of the heart and the voltages detected on the body surface may be viewed in the forward or inverse direction. The solving of these relationships is referred to as the "forward problem" and the "inverse problem". The "forward problem" is the translation of the state of the source of the transmembrane voltages, or the cardiac generator, to the potential at the body surface. Theoretically, the forward problem can solved directly provided enough information is given about the generation of transmembrane potentials, the propagation of the cardiac wavefront within the heart, the transmission of the potentials through the non homogeneous conductive medium, and the potential at any irregular boundaries. In real world applications this information is virtually impossible to accurately attain.

TABLE 1-1 Transmission Factors

A. Physiologic Factors
   1. Cellular factors
      a. Intracellular conductivity
      b. Extracellular conductivity
      c. Ion concentrations
   2. Cardiac tissue factors
      a. Connective tissue
      b. Anisotropy
   3. Organism factors
      a. Intracavitary blood
      b. Ventricular wall thickness
      c. Pericardial tissue and fluid
      d. Lungs
      e. Skeletal muscle
      f. Fat

B. Biophysical factors
   1. Distance
   2. Boundaries
   3. Cancellation

In the inverse problem the opposite situation occurs. Given an accurate and comprehensive body surface potential map one attempts to find the state of the cardiac generator. In this case the data, a body surface potential map, is relatively simple to obtain. The difficulty which occurs is that this problem, unlike the forward problem, has no unique solution. For every potential map there exists an unlimited number of states for the cardiac generator. In addition to accurately sampling the data, the analysis must involve making certain inferences about the heart's condition. It is the solving of the inverse problem which is the focus of BSPM.

While body surface potential mapping provides greater spatial detail than the standard ECG, it is still basically a research tool. It is yet to be utilized in clinical applications due to a number of shortcoming in current methods. These shortcoming arise

from the complexity and non-uniqueness of the inverse problem. Advancements in electrocardiography are presently occurring which will provide for the transition of these methods to clinical environments. The software system for this project utilizes a number of these advancements to make this transition more feasible.

1.3 Body Surface Laplacian Mapping

One shortcoming of body surface potential mapping is its inability to portray multiple simultaneous bioelectrical events in the heart. This is due to a smoothing effect of the volume conductor which makes it difficult to identify the location and magnitude of single events. The solution to this problem developed by He and Cohen is know as body surface Laplacian mapping[12]. Under this approach cardiac electrical activity is measured by taking the surface Laplacian of the potential on the body surface. Comparisons between these Laplacian maps and their corresponding potential maps show an improved distinction of localized spatial events in the Laplacian maps. There is also a significant improvement in the signal-to-noise ratio in the time domain for individual points on Laplacian maps.

He and Cohen utilized two methods to create a Laplacian map. The first was to simply to derive the BSLM mathematically from the BSPM. Under this method the Laplacian value for a given point 0 can be found using the following equations:

$$\begin{aligned}\nabla^2_{xy}\phi &= \partial^2\phi/\partial\phi x^2 + \partial^2\phi/\partial\phi y^2 \\ &= \partial(\partial\phi/\partial x)/\partial x + \partial(\partial\phi/\partial y)/\partial y \\ &= [(\phi_1 - \phi_0)/b^2 - (\phi_0 - \phi_3)/b^2 + (\phi_2 - \phi_0)/b^2 - (\phi_0 - \phi_4)/b^2] \\ &\equiv (4/b^2)\,[(1/4\ \Sigma\ \phi_i) - \phi_0] \text{ for } i = 1,2,3,4\end{aligned}$$

where b is equal to the distance between electrodes on Cartesian coordinate grid and ϕ_1 through ϕ_4 are the potential recorded at channels closest to point 0. For the approximation to be valid b must be sufficiently small.

The second way used to generate BSLM was using electrodes specially developed by He and Cohen[13]. This electrode is called the integrated bipolar electrode and consists of a central conductive disk surrounded by a concentric circular conductive ring, both components are made of AgCl. The area between the disk and the ring acts as an electric insulator. The output for this electrode is simply the difference between the average potential of the disk and the average potential of the ring. The electrode uses the following Laplacian formula for a circular area:

$$\nabla^2_{xy}\phi = (4/b^2) \left[(1/2\pi b) \int \phi \, dl - \phi_0 \right]$$

The surface areas of the inner disk and the outer ring are identical to balance any electrochemical processes between the electrode and the skin.

The software developed for this thesis utilizes both the derived method and the bipolar integrator electrode method. The software calculates Laplacian maps from body surface potential maps as well as provides for the input of data attained with the special bipolar electrodes.

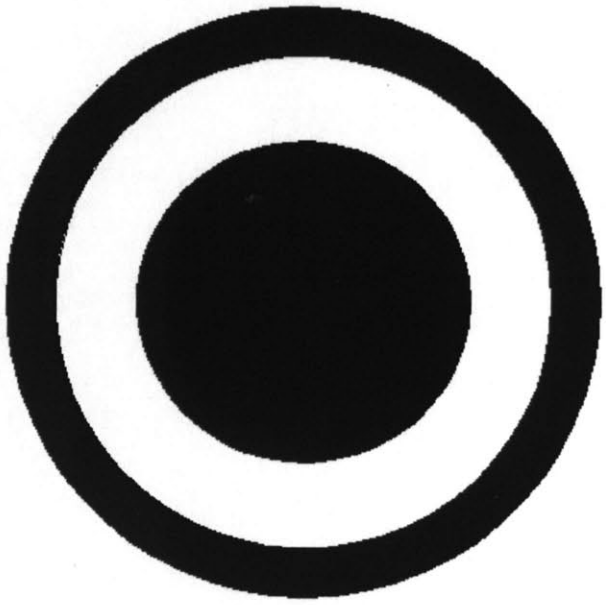

Figure 1-2: Schematic diagram of the circular bipolar Laplacian electrode structure[12]. The shaded area consists of AgCl. The white area is an insulator. The surface area of the central disk was set to be the same as that of the outer ring.

Chapter 2

Imaging Applications

2.1 Background on Current Software Applications

The software currently available at MIT to analyze BSPM and BSLM was developed in C and designed to run on the MassComp 5450, a 68020 based workstation running a real-time Unix kernel. There are presently few standard systems on the market which perform its functions. This software is basically used only for the purpose of research. It is yet to be implemented in a clinical environment.

The application provides for both temporal and spatial analysis of body surface potential signals. It allows the user to view the voltage signals generated by multiple and individual channels of a given data file. It is also capable of producing contour maps for potential and Laplacian plotting. The software grants the ability to make these contour

maps animate or move with time. The system allows the user to create new data files by altering an already existing data file using time and space domain adjustment functions.

2.2 Body Surface Mapping in a Clinical Environment

The present widespread use of electrocardiographic mapping is hampered by a number of limitation[16]. First, a lack of a standardized system exists. The number and placement of electrodes on the thoracic area varies from one laboratory to the next. This inhibits communication between researchers. Second, there is a scarcity of automated data acquisition instruments. Making the use of this equipment too expensive for the vast majority of clinical environments. Also, the data exchange between these systems and other computers is often not possible, once again inhibiting communications. Third, the physical geometry of torso varies from subject to subject. This adds a further level of complexity to the "inverse problem". The measuring and accounting for these difference is a time-consuming and inexact process.

The clinical use of body surface mapping provides for many benefits. The first, most obvious, advantage is the earlier and more comprehensive detection of cardiac diseases and abnormalities. Another is the creation of a common database for statistical evaluation. This aids the research field by providing a much larger sample set to apply multivariate discriminant analysis on the categories of age, sex, body build, race, height, and coexisting heart disease.

For the integration of electrocardiographic mapping into a clinical environment to be achieved a cost efficient solution must be provided. The development of image processing and high-resolution mapping software for a desktop computer will play a major

role in achieving this goal. By utilizing high-performance low-cost PC and standard user-friendly operating systems we were able to develop a software system with features nearly identical to existing high end computer systems.

2.3 Project Goals

The primary goal of the work of this particular thesis was to develop a electrocardiographic image processing software system on a low-cost desktop computer. This would reduce the cost of further projects by eliminating the dependence on an expensive UNIX machine. The data files used on a PC would be more portable than the data on the existing system. The software interface could also be easily developed in a standard user-friendly environment. This would allow for its use by individuals in the medical field without a high-degree of computer literacy. These three factors of cost, portability, and usability will make the eventually movement of electrocardiographic mapping into a clinical environment much more feasible. It is also important to make data generated by the software to have forward and backward compatibility with the UNIX version.

The first step of this project was to research and select the language, machine, and operating system for which this application would be best suited. The machine chosen was a IBM-clone 386 with the operating system of Microsoft Windows. The 386 computer was chosen due to the dominance of the 80x86 series in desktop computing. Windows provided a very user-friendly familiar environment which would allow for a flatter learning curve for new users of the software. Windows has become the operating systems of choice in a variety of settings. It appears that both these products will have a strong position in the market place in upcoming years. This will allow the distribution of

our software into the clinical setting to be more feasible. C was chosen as the application's language also for its widespread presence, in addition to the fact that it was the language of the original UNIX system. The tools selected for this project were the Microsoft C 7.0 compiler and the Microsoft Window's Software Development Kit. A secondary goal of this project was to introduce these tools into lab for future development activities.

2.4 General Software Considerations[15]

With the use of Window's menu system and dialog boxes all operations of this particular system are easily provided for through the use of the mouse and number pad. The operator selects all commands through pull-down menus and enters all parameters into dialog boxes created within the program. The files are selected through the use of a standard Windows file selection dialog box which creates a directory-based selection list for all current files. All decision involving the selection of a particular signal or the selection of a particular time of a signal is accomplished by using the mouse to click directly on to the waveform. When this is necessary the cursor changes from the standard arrow to the crosshairs symbol, '+'. The system contains three main windows for different types of analysis. The first is to display and perform primarily spatial analysis and mapping. The other two perform temporal analysis and signal display. These are as referred to as **multiple channel analysis, single channel analysis, spatial analysis** windows. The user when appropriate is given the ability to switch back and forth between these windows. The flow of the overall software can be seen in Figure 2-1.

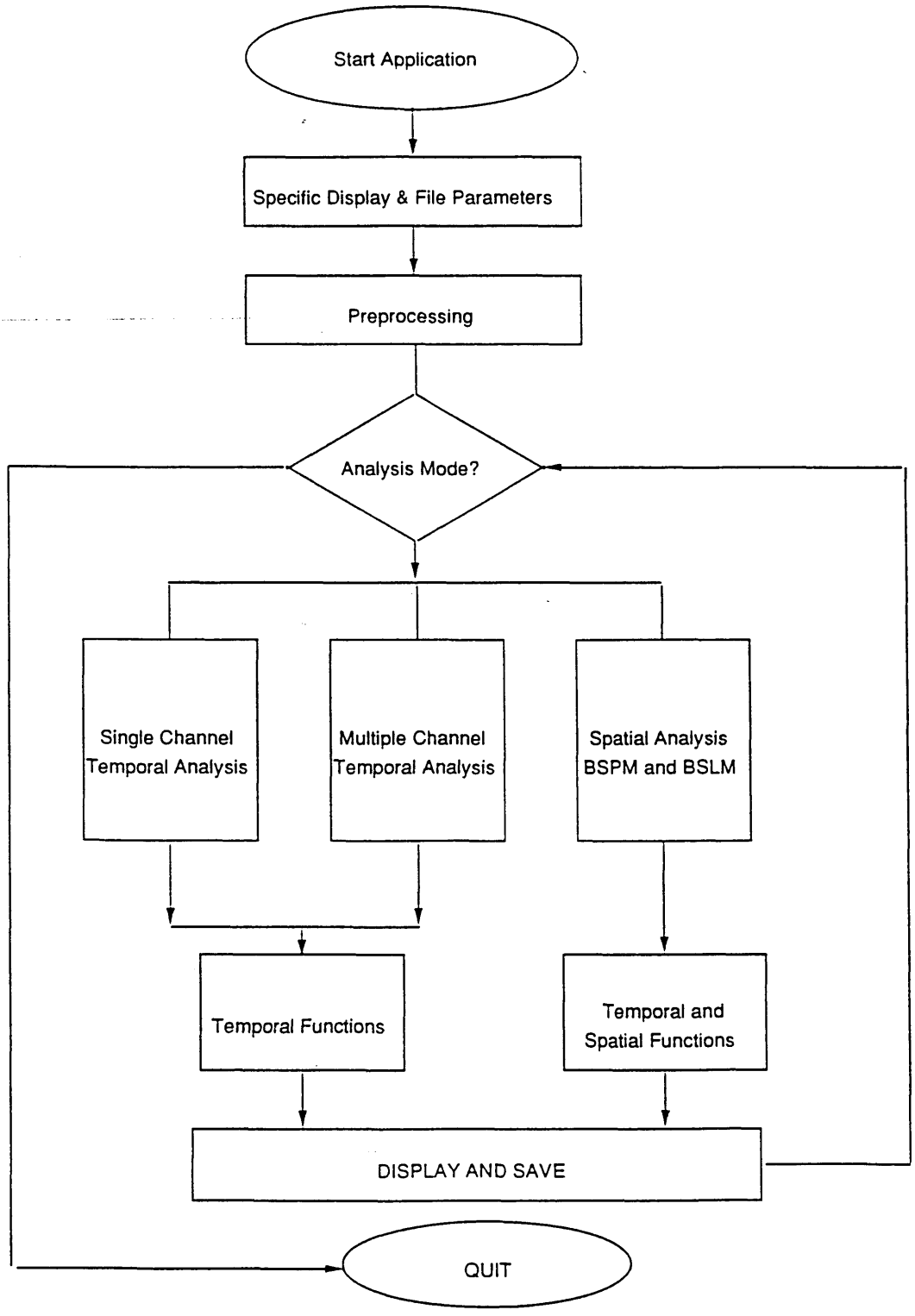

Figure 2-1: Overall Flow of Software: The user has the capility to perform signal processing functions, generate body surface contour maps, and manipulate and store data.

For every set of test data two files exist, a header file and a data file. The header file contains recording information (frequency, number of channels, number of records, number of frames, or samples, per record). The program has the ability to read three different types of header files. They are referred to in the program as the LWB, the BH, and the Animation format. The LWB format files are created in the Laboratory Workbench, which is a popular program provided by MassComp for driving data acquisition. The BH format files are generated by the software of this application and its equivalent UNIX application. It is short file listing only information necessary for the implementation of this software. The Animation format is created and read only in the **spatial analysis** window. In addition to the information contained in the BH file format, the animation file format also contains the dimensions of the contour map and the initial and final frames of the animation. A more detailed description of the animation feature will be given in Chapter 4. The BH and animation file formats can be viewed in Figures 2-2 and 2-3.

```
# Channels   :     64
# Frame Size :    250
# Secs/Frame :   1.00
# Records    :      1
```

Figure 2-2: The BH header file format.

```
# Channels        :   441
# Displayed Channel :     3
# Records         :     0
# Frame Size      :   500
# Secs/Frame      :  1.00
# Initial Frame   :   147
# Final Frame     :   161
# X-Map Dimension :    21
# Y-Map Dimension :    21
```

Figure 2-3: The Animation header file format.

The data file is a binary file listing of short integers. The data file first lists the potentials for all the channels, in order, for the first frame of the first record. The file then contains the potentials for the rest of the frames of the first record, and then begins listing the data of the next record. To allow this information to be read by both PC and the UNIX adjustments to the software were required. This is due to the way in which each platform reads and stores binary data files. The bytes for a two-byte short integer are in the opposite order or flipped on each system. In the UNIX system the high-order bytes are read first, while under the PC system the low-order bytes are first. To solve the problem a dialog box was created which prompted the user to indicate the format of the file to be read or saved. When necessary, the bytes would be individually flipped for every short integer through the use of a simple procedure shown in Figure 2-4.

```
VOID PASCAL FAR ShiftBits()
/*This Procedure shifts bits for a UNIX file*/
  for (rec = 0; rec <= records; rec++)
   for (cha = 1; cha <= channels; cha++)
    for (fra = 1; fra <=  frames; fra++)
     {
     a = Data[rec][fra][cha] << 8;
     b = (Data[rec][fra][cha] >> 8 & 0xff);
     Data[rec][fra][cha] = a | b;
     }
```

Figure 2-4: The procedure ShiftBits changes the data format of binary files from PC files to UNIX files.

Chapter 3

Temporal Analysis and Display

3.1 Display and User Parameters

The initial window displayed when the application is opened is the **multiple channel analysis** window. It allows the operator to simultaneously view all or a subset of the channels for a data file. The user has the ability on this window as well as the others to select the parameters of the display through the use of a dialog box referred to as the imaging control panel. This panel prompts the user to select the vertical and horizontal dimensions of the grid on which the signals are displayed, the display channel for single signal situations, the format of the file(PC or UNIX), and the data file type(Potential or Laplacian). This control panel is shown in Figure 3-1. The signals will then be numbered starting in the upper left-hand corner and moving down then across. If the user requests fewer signals than exist in the data file the last channels are not displayed. If the user requests more signals than exist in the data file extra signals are displayed containing values of zero at every point. From this screen the user has the

ability to use the following temporal functions: **baseline adjustment, trend adjustment, amplitude increase and decrease, 3-point and 5-point moving average filters, and artifact removal**. To select the necessary points and channels the selections are made by clicking on the signals in the manor mentioned above. These operations are detailed in Section 3.2. The present system has a maximum channel display limit of 625 or 25 channels in either dimensions. The numbering of the channels will take place when less than 400 channels are displayed. The multiple channel display window is shown in Figure 3-2.

From this window the user has the option to go to the **signal channel analysis** window. On this window the user sees one channel's signal which dominates the entire window. Along with this signal the units scaling appears on each axis. Along the vertical axis for a potential data file the units of mV(millivolts) are shown. If the file is a Laplacian data file units of mV/mm^2(millivolts per square millimeter) appear. Along the horizontal axis the units of ms(milliseconds) are displayed. The single channel display window is shown in Figure 3-3. On the single channel window the following functions can be used **baseline adjustment, trend adjustment, amplitude increase and decrease, 3-point and 5-point moving average filters, and change display channel.**

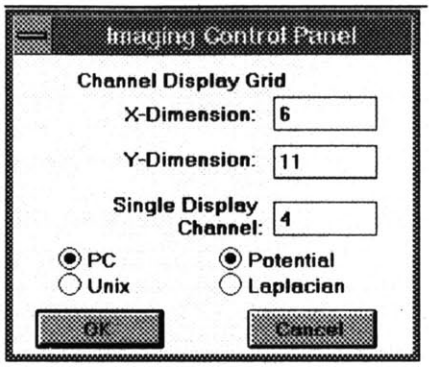

Figure 3-1: The initial control panel for the BH and LWB header formats

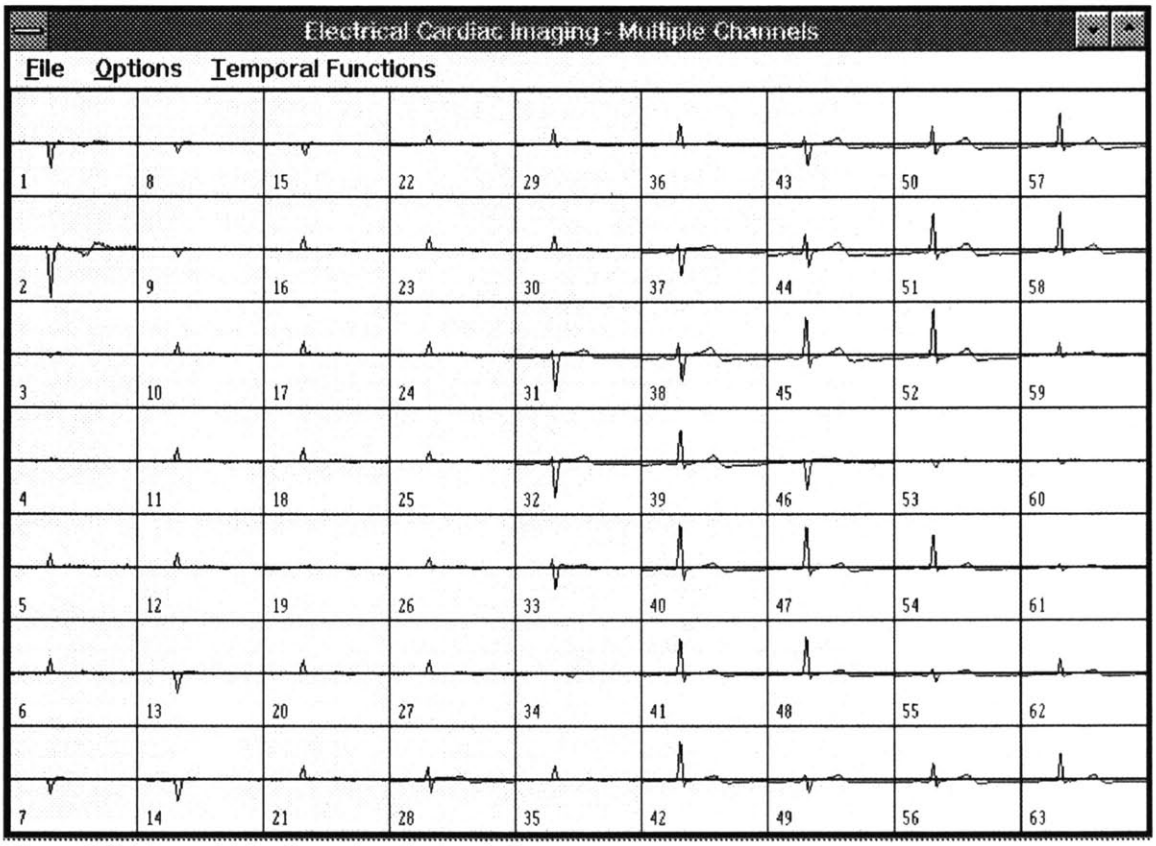

Figure 3-2: The multiple channel analysis window.

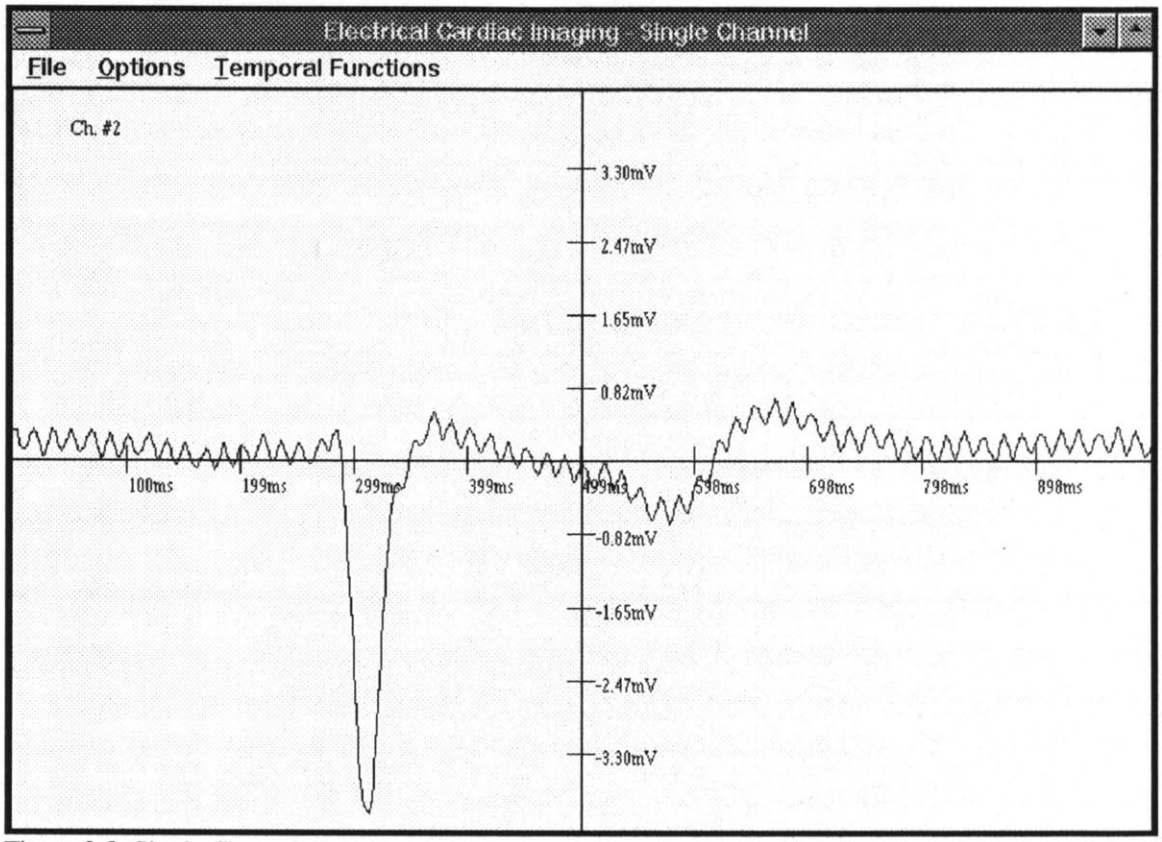

Figure 3-3: Single Channel Analysis Window

3.2 Functions[15]

3.2.1 Baseline Adjustment

The presence of this function is vital for signal processing analysis. It is used to select a defined instant or instants which will correspond to the zero potential level and adjust all data points in relation to this voltage. This could be used in a case where during data acquisition a constant DC voltage occurred across all channels. In cardiac activity the ideal baseline point would be at the time where the cardiac current equals zero. This is usually during the time period between the T and P waves of the cardiac cycle. The user chooses a baseline point by selecting the a range of points for one channel. The potentials at these points are then averaged. The value of this average then becomes the zero potential point.

Algorithm A: Baseline Adjustment

A-1 → The user selects the first and last points for a single channel.

A-2 → The average voltage is calculated for the range between these two points.

A-3 → The average voltage is subtracted for all points on all channels for all records.

A-4 → The necessary adjustments are made to dependent variables and the display.

3.2.2 Trend Adjustment

A **`trend adjustment`** is necessary when an increasing or decreasing linear voltage occurs across a set of data for all channels. The functions is similar to the baseline adjustment in that two end points are selected. In this case rather than averaging the points the procedure calculates the line of best fit for the points. The points of this line are

then subtracted from every channels of each record. The line of best fit for a set points (X,Y) where X is the number of the frame and Y is the frame's potential can be describe as

$$Y = \beta_0 + \beta_1 X$$

where

$$\beta_1 = \frac{\sum (X_i - \overline{X})(Y_i - \overline{Y})}{\sum (X_i - \overline{X})^2}$$

$$\beta_0 = \overline{Y} - \beta_1 \overline{X}$$

$\overline{X}$ is the average value for the frame number

$\overline{Y}$ is the average value for the potential of the frames

Algorithm B: Trend Adjustment

B-1 → The user selects the first and last points for a single channel.

B-2 → The average voltage and average frame is calculated for the range between these two points.

B-3 → The slope and offset is calculated for the line of best fit.

B-4 → The line of best fit is subtracted from each frame of all the channels.

B-5 → The necessary adjustments are made to dependent variables and the display.

3.2.3 Amplitude Increase and Decrease

The amplitude increase and decrease functions allow the operator to multiply or divide all the voltages of a single channel by a user-specified integer value. The purpose of this function is to allow the user the ability to better analyze a signal at levels much lower than the maximum for a given data file. When the potential of any points on the data file will be increased beyond the value of the original maximum of the data file, the value of the potential of those points are set equal to the maximum. This function never increases the maximum or decreases the maximum. When this function is called the user first clicks on channel he would like to modify after which a dialog box pops-up requesting the scaling factor.

3.2.4 Moving Average Filters

Another important feature of this system is the ability to remove AC line noise. To do this the software uses three-point and five-point moving average filters. In this type of filter, each data point is replaced by the average of its former value and the surrounding two or four points, respectively. The frequency of the lowest zero value of the filter can be found using the formula

$$f_{stop} = \frac{f_{samp}}{\omega}$$

where f_{samp} is the frequency at which the data is sampled and ω is the width of the filter, 3 or 5 points, in this case. f_{stop} is the frequency of the lowest zero at which the AC line noise will be eliminated. AC noise will also be eliminated at all multiples of f_{stop}.

3.2.5 Artifact Removal

For some data sets it is necessary to remove a faulty channel or set of channels. This may be due to problems with a channel's electrode, wiring, or placement. The faulty data can be replaced by the potentials of another channel or the average potentials of a set of channels. The user performs this operation by first clicking on the faulty channel, and then clicking on the set of channels used to replace this channel. The set of channels is typically made up signals which are adjacent to the artifact channel.

Algorithm C: Artifact Removal

C-1 → The user selects the channel to be removed.

C-2 → The set of channels used to replace the artifact is selected.

C-3 → The average of the potential for every frame of the of channels is calculated.

C-4 → The calculated averages are placed in the buffer of the artifact channel.

C-5 → The necessary adjustments are made to dependent variables and the display.

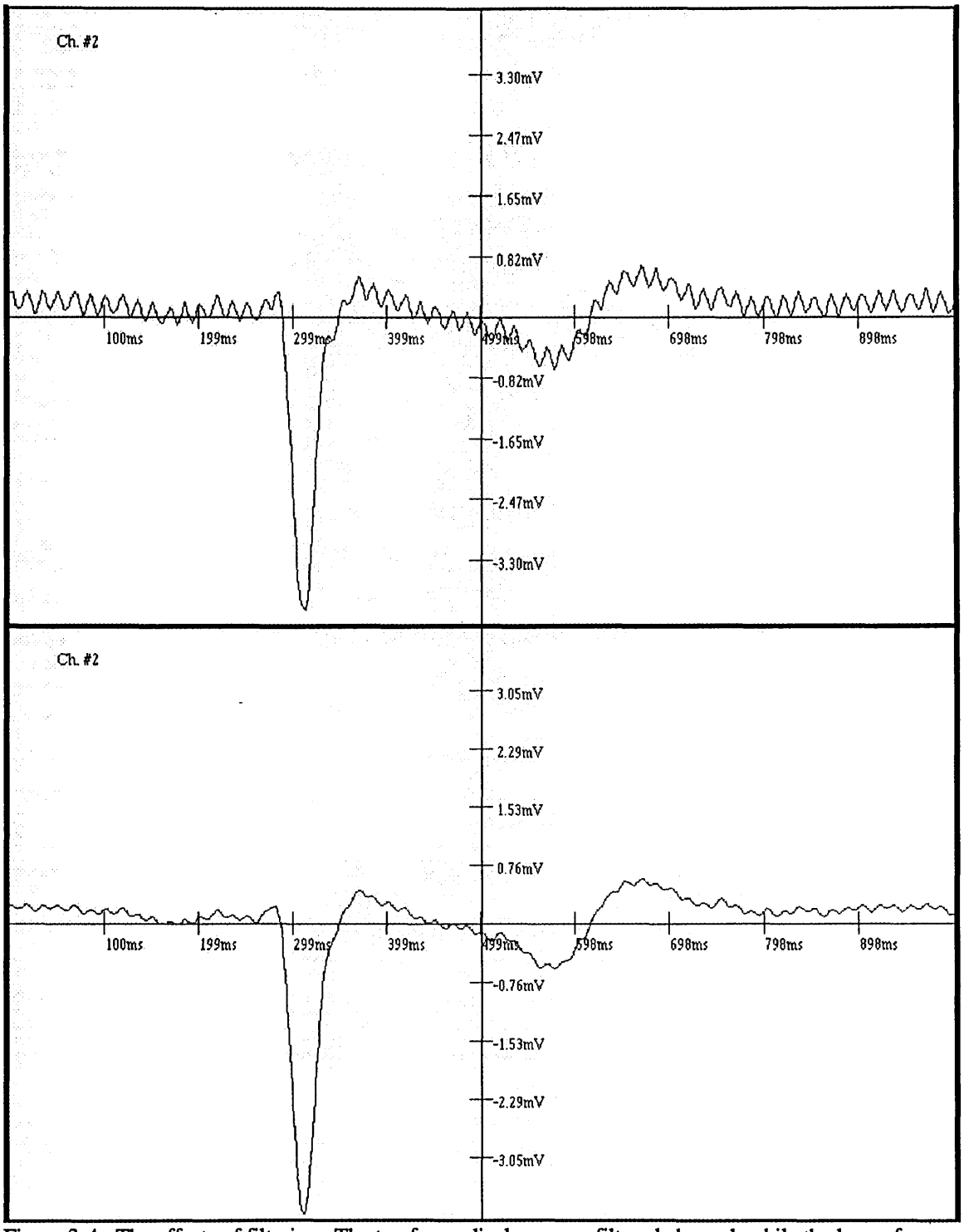

Figure 3-4: The effects of filtering. The top frame displays an unfiltered channel, while the lower frame represents the same signal after it is passed through two 5-point filters.

3.2.6 Change Display Channel

This function simply changes the channel displayed on the **signal channel analysis** window or the **spatial analysis** window. This is done through the use of a dialog box which requests the channel number. If the channel entered doesn't exist, an error message box pops-up and the dialog box is redisplayed.

Chapter 4

Spatial Analysis and Display

4.1 User Display Parameters

The third analysis window is referred to as the **spatial analysis** window. On this window the user has the ability to view the signal of a single channel in addition to a potential or Laplacian map for all or part of the channels. On the far right side of the screen a color scale key appears indicating the colors and their corresponding potential levels. A rectangle is draw in the map space for a given channel in a color corresponding to that channel's potential on the color scale. This provides the analyst with greater spatial detail. The application also contains three different color scales which can be rotated with the menu command, **change color key**. Like the **multiple channel analysis** window, the user can select the dimensions of the channel display. Also like the **multiple channel analysis** window, the extra channels are set to zero when too many channels are entered, and the end channels are not displayed when too few channels are entered. Since a single display signal appears at the bottom of the screen, the

operator has access to all the temporal functions of the single channel window. On this screen the user has access to nearly of the functions of this system. The software flow of this analysis mode can be observed in Figure 4-1.

The strength of mapping function of this system is the ability to quickly view maps at different time points and animate the maps in the time domain. This window contains the spatial functions: **select time, forward animation, backward animation, local normalization, gain adjustment, linear interpolation, and Laplacian generation**. The user also has to read and save special files called animation files. The spatial analysis window is shown in Figure 4-2.

4.2 Functions[15]

4.2.1 Select Time

This function allows the user to skip around to maps corresponding to a selected time point. When the user selects this function the user is prompted to click on a time point on the reference signal. The corresponding map for this time point will then be displayed. This is a very convenient for studying features of interest that appear on the reference signal.

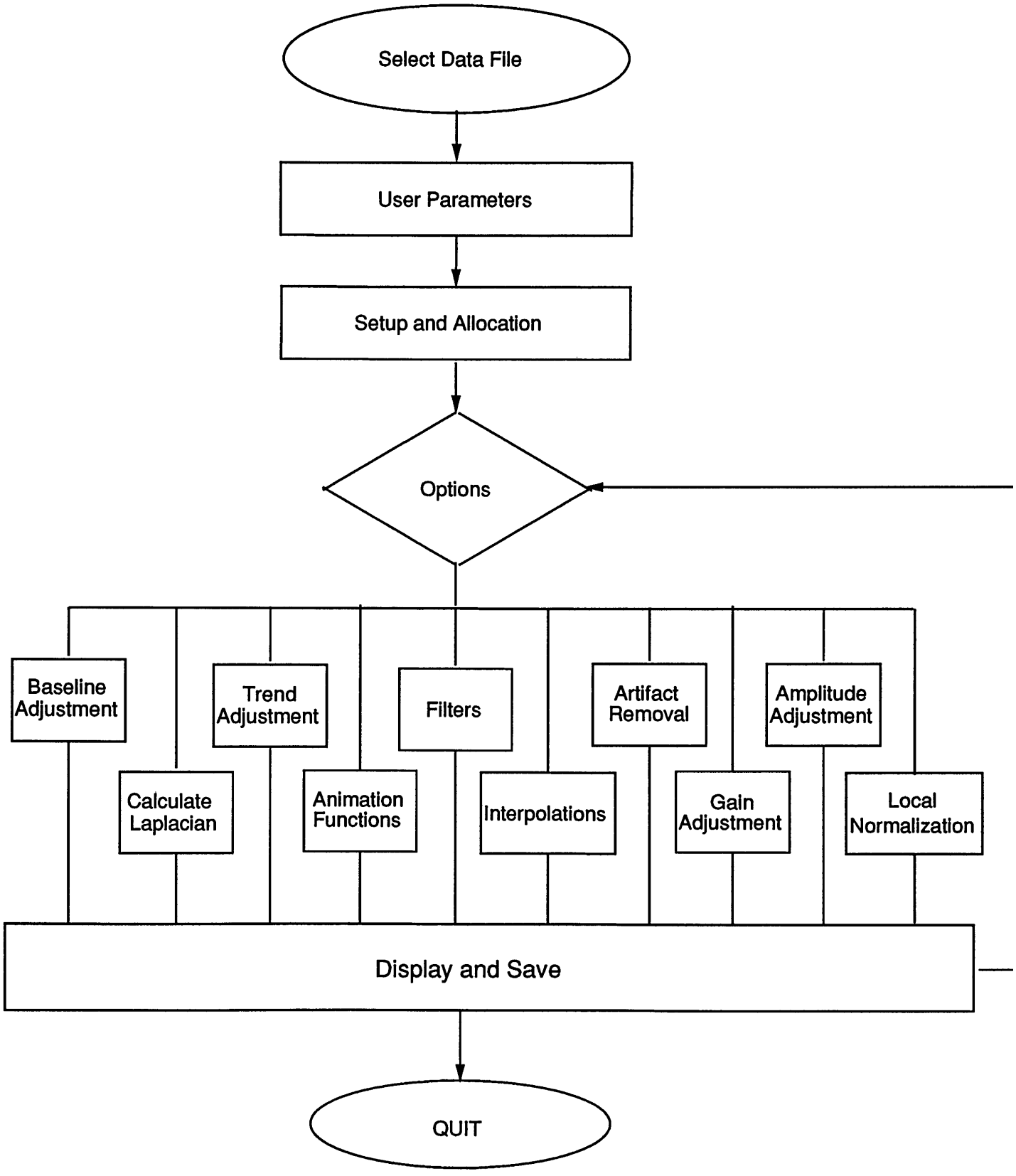

Figure 4-1: Flow of Temporal and Spatial Analysis Functions

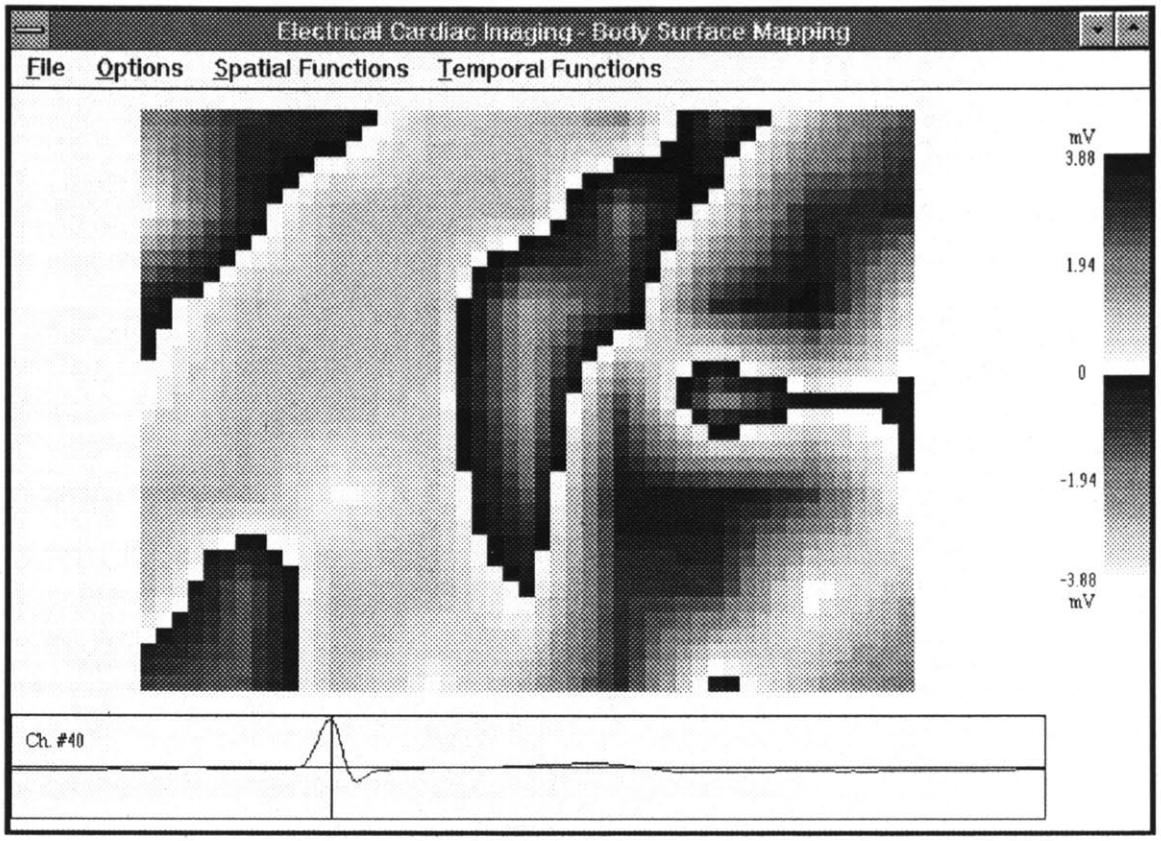

Figure 4-2 The spatial analysis window.

4.2.2 Forward and Backward Animation

Forward animation is simply the ability to continuously view the maps of the next sequential data points. The user has the ability to adjust the speed of the animation using the commands **animation speed increase** and **animation speed decrease**. The animation concludes when the user selects **stop animating**, a forward animation reaches the final frame of a record, or a backward animation reaches the initial frame of a record. At times when very large data sets are used or a large number of mathematically intensive interpolations are being done maps may be displayed at rates slower then the intended speed. The animation file format can be used to solve this problem.

4.2.3 Gain Adjustment

Since there are 64 colors in this program each color represents a range of potential which is 1/64th of the potential range of the entire data set. The potential range for all the data is equal to twice the maximum voltage. Using this standard set-up it is difficult to view distribution details that take place at low voltages. It is not uncommon for significant events to occur at potential levels magnitudes smaller than the peak voltage for the entire data set. To solve this problem the **gain adjustment** function was created. The **gain adjustment** function requests a scaling factor from the user, and then multiplies all the data points for a displayed map by that factor. Like the **amplitude increase** temporal function, this function also doesn't change the maximum. All instants where the absolute value of the multiple of the original potential and the scaling factor is greater than the maximum are set to the maximum. The map can be returned to its original color scheme by recalling this function and entering 1 for the scaling factor.

Algorithm D: Gain Adjustment:

D-1 → The user selects the scaling factor for a map.

D-2 → All the points on the present map multiplied by the scaling factor.

D-3 → Potentials at points above the maximum are reduced to the maximum.

D-4 → The scaling factor is stored for use on future maps.

4.2.4 Local Normalization

Another way to alter the color scaling to view greater detail at low voltage levels is through the **`local normalization`** function. When using this function the user selects a range of points on the display channel by clicking on two end points. The program then finds the maximum value between these two points for all the channels of all the records. This new maximum then becomes the maximum value on the color scale for all future maps. If the maximum voltage for user-selected range is exactly half the magnitude of the peak voltage for the entire data set, then this function is the equivalent to entering a value of 2 into the **`gain adjustment`** function. Once again, if a future point with the value above the local maximum is requested, it is displayed with the maximum positive or maximum negative color. The color scheme can be returned to normal by entering a one into the **`gain adjustment`** function or selecting the local normalization function and selecting a range containing the peak voltage for the data set.

Algorithm E: Local Normalization:

E-1 → The user selects a range of points on the display channel.

E-2 → The maximum for potential within this range for all channels is found.

E-3 → The map is redisplayed with the local maximum becoming the map's maximum.

E-4 → The local maximum is stored for use on future maps.

4.2.5 Linear Interpolation

One of the important aspects of mapping software is its ability to increase the resolution of the display maps by interpolating values at positions in between electrodes. It has been shown that many electrodes record redundant information, therefore it is more efficient to record data using fewer electrodes, and then mathematically estimate the value of the potential in the area between the electrodes. Linear interpolation is one of the most straight-forward and efficient ways of accomplishing this. When using this function it assumed that the potential change between two adjacent recorded points is linear. The potential at point x between known values at points x_j and x_{j+1} can be found using the formula

$$f(x) \cong Af(x_j) + Bf(x_{j+1})$$

where

$$A \equiv \frac{x_{j+1} - x}{x_{j+1} - x_j} \qquad B \equiv \frac{x - x_j}{x_{j+1} - x_j}$$

When this function is called a dialog box appears requesting the user to enter the number of points, *n*, between each set of adjacent channels to be calculated. The dimension of the rectangular channel grid will then change from M by N to (M-1)**n* +1 by (N-1)**n* +1. The only limit on the number of interpolations possible is due to constraints on the graphics screen. If the system calculates that the size of the area used to display a single point will be smaller than a single pixel, an error message will appear and an interpolation number will again be requested. To return the map to its original form an interpolation number of zero must be entered into this function.

4.2.6 Animation File Format

The combination of a large number of interpolations and the request for **forward animation** or **backward animation** will cause the system to perform very slowly. This is due to the large amount of mathematical analysis which must be done concurrently with a number of screen redraws. To correct this problem the software allows the user to save a portion of interpolated data to a file, and perform an animation without having to reperform the calculations. This file format can only be saved and read from the **spatial analysis** window. An animation file format can only be saved after an interpolation can has been perform. Along with the animation file the entire data buffer for the display channel is also saved.(This is an advancement over the UNIX system which is not presently compatible.) When the save command is called the user indicates where he would like the animation to begin and end as well as the name of the new file. A header file is then created containing the following information: the number of original channel, the number of records, the number of frames, the initial frame of the animation, the final frame of the animation, the dimension of the contour map after the interpolations had been performed. In the binary data file the information for the contour map is saved first, followed by the data for the display channel.

When a animation file becomes the current file only the following functions available to the operator are **select time, forward animation,** and **backward animation.** The screen can now be redrawn at a much faster rate than while the interpolation was be performed. If the user chooses the **select time** function and then chooses a time point outside the range of the animation, a warning message appears and the user is returned to the map of his previous time point. A message is also displayed during a forward or backward animation when the final or initial frame is reached.

4.2.7 Laplacian Map Generation

The user has the ability to read and display BSLM in two ways discussed in Section 1.3. Under the method involving the special electrodes the user selects the Laplacian button on the imaging control panel when appropriate. The derived method can be used only in the **spatial analysis** window. The user has the ability to calculate both the five point and nine point Laplacian. The formula for the five point Laplacian is shown in Section 1.3. The formula for the nine point Laplacian simply takes into account the four additional points which are diagonal to every calculated point. Both the commands change the dimension of the display grid from M by N to M-2 by N-2, since the Laplacian can not be calculated for points on the perimeter of the grid.

When one of Laplacian commands is selected the user has the option of calculating the Laplacian for the entire data set or for only the currently displayed map. If the user chooses to calculate the Laplacian for the entire data set, which is obviously quite time consuming, the Laplacian wave form of the display channel will be shown. The user then also has the ability to enter the multiple channel window and the single channel window to view the Laplacian wave forms for other channels. If the user decides to use either Laplacian function, all future maps will be Laplacian maps.

Chapter 5

Conclusion

A user-friendly, portable software system has been developed which provides a wide range of functions for electrocardiographic signal and image processing and visualization. This system will be immediately utilized at MIT for further studies involving body surface potential mapping. While the software accomplishes all the goals proposed in Section 2.3 and the system performs all the functions specified in Sections 3.2 and 4.2, it only an initial step in the full utilization of body surface mapping in a clinical environment. A number of advances in the mapping of cardiac fields are still required before its widespread application becomes practical. A number of technical problems in data acquisition, display, and interpretation in terms of intracardiac events are presently being solved. As new methods are found, they can be quickly adapted to the software of this thesis.

The beta testing of the system in a handful of clinical environment should also play a major role in its future development. This testing would immediately accomplish at least three things. First, direct feedback from the clinical sources could be received about the

usability and functionality of the system. Second, an immediate database would be established of a broader subset of the population than now exist through laboratory research. This would allow for statistical analysis which could provide for improvements in the electrocardiographic model. Third, a greater understanding of electrocardiographic mapping would be attained by the clinical field.

When this software is first utilized in a clinical environment, the primary goal of the focus of this thesis will be accomplished. This goal is to utilize body surface mapping efficiently in clinical applications, and to use feedback from the clinical environment to aid in future developments in the experimental field of electrocardiographic mapping.

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