Presentation and Analysis of Vector Electrocardiograms

Anna Redz

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Abstract

This master thesis describes a study of vector electrocardiograms, conducted for Ortivus Medical AB. Ortivus has developed a monitoring system called MIDA, that is used for supervision of heart patients. The MIDA system displays derived 12 lead ECG curves and three orthogonal projections of the vectorcardiographic loops. It calculates several parameters from the loops and presents them as functions of time, *trends*. The trends are used as an aid in diagnosing patients. The thesis describes possible improvements of the MIDA system.

A VCG loop is three-dimensional. The first improvement consisted in presenting the loop so that it is easy to perceive its form. It was done by plotting the loop into a rotatable Cartesian coordinate system. The second improvement was to normalize the loops. Based on another study [Fayn et al., 1983], all the loops were normalized to coincide maximally with the first loop measured on the patient. MIDA parameters were calculated based on the normalized loops. Some new parameters were invented to enable the study of some other features of the loops.

A very small study based on five patients (2 infarctions, 1 instable angina (a heart condition), 2 undiagnosed but with documented changes of body position) showed that the MIDA parameters based on normalized loops may be better indicators of ischemia then those calculated on unnormalized loops.

Further studies are being made to evaluate the parameters.

Contents

Chapter 1

Introduction

This master's thesis deals with vector electrocardiograms (vectorcardiograms, VCGs). An electrocardiogram shows the hearts electrical field as a function of time (see 3.2). It reports a study conducted for Ortivus Medical AB. Ortivus Medical AB has developed a monitoring system, called MIDA, that is used for supervision of heart patients in many hospitals around Sweden and the rest of Europe. Today, the MIDA system monitors the surface ECG signals and displays derived 12 lead ECG curves and three orthogonal projections of the vectorcradiographic loops. Special MIDA parameters are calculated from every loop and are presented as functions of time, *trends*. These trends are used for diagnosis.

The MIDA system is continuously improved and updated to meet the customers' demands. This master thesis describes four possible improvements, all intended to assist the diagnosis of heart malfunction.

Olle Bälter from Nada and Gunilla Lunddahl from Ortivus Medical AB where my thesis advisors, who together with my father helped me with many difficulties in my master's thesis.

Chapter 2

The Problems

The problems considered in this thesis are: graphical presentation of VCGs, normalization of VCGs, new and recalculated old parameters computed from the VCGs and localization of ischemia (lack of oxygen).

2.1 Graphical Presentation of the VCG

A vectorcardiogram has the form of a three-dimensional loop, and contains information about the heart's condition. In order to make doctors accept and use the vectorcardiogram, it has to be presented in a way that is easy to understand. Traditionally these loops are presented as projections on three orthogonal planes. It is very difficult to get a clear picture of the real three-dimensional form of the loop using these projections.

Therefore the loop should be presented so that it can be rotated freely to enable study of the loop's form. The position of the loop in relation to the human body should be shown.

2.2 Normalizing the VCGs

Today (in MIDA1200), the loops are uncritically compared with the first loop measured on the patient. This comparison does not take into account possible changes resulting from different position of the patient or of inexact placement of the electrodes.

It is suggested [Fayn et al., 1983] that these factors can be eliminated if only the *shapes* of the loops are compared. May this simplify the analysis of the ECG and VCG?

2.3 Old and New Diagnostic Parameters

When old MIDA parameters are recalculated from the altered loops, do they change much and do they give us new information? Can any new parameters be calculated from the vectorcardiograms to give us better or new information about what is happening in the heart?

2.4 Presentation and Location of Ischemia

Ischemia is lack of oxygen in a muscle, and is usually caused by lack of blood flow. An approximate location of ischemic area can be found by studying the ECG.

A method of presenting the exact location of the ischemia and its size was to be studied and developed.

Chapter 3

The Heart

The heart works as a circulatory pump for blood in our bodies and is driven by electric signals. These signals can be registered at the surface of the body and can be used to diagnose the condition of the heart. This procedure is called electrocardiography.

3.1 Anatomy and Function

The heart consists of two chambers, *the ventricles* and two antichambers, *the atria*, where the blood is stored while the ventricles are working [Webster, 1992].

For the heart to function as a pump, its different parts must contract in a well defined and well-timed sequence. This sequence is controlled by electric signals spreading through the heart. The signals originate in the sinoatrial node (the SA node). The SA node consists of pacemaking cells whose frequency is regulated by the autonomous nerve system. The heart muscle is built from cells electrically connected to each other (this is unlike other muscles, which have to be stimulated via a nerve). The heart contains a layer of isolating cells between the atria and the ventricles. This layer of cells prevents all electrical communication between the atria and the ventricles except through the atrioventricular node (AV node), where the electrical signal becomes slightly delayed. [Arvill; Jacobsson, 1987; Webster, 1992; Jern, 1987].

3.2 The Electrocardiogram and the Vectorcardiogram

Each cell in the heart can be represented as a dipole with differing direction throughout the heartbeat. A collection of all these small dipoles close to each other can be represented as a single dipole. The electric field of the heart can then be studied as a field of a single dipole, *the cardiac vector*. The line drawn by the tip of the cardiac vector is the vectrocardiogram (VCG). During a heart beat the tip draws a collection of three-dimensional loops, called a VCG complex or a VCG loop. Measurements on the body surface give information about the dipole inside. The measured signals are used to reconstruct the cardiac vector

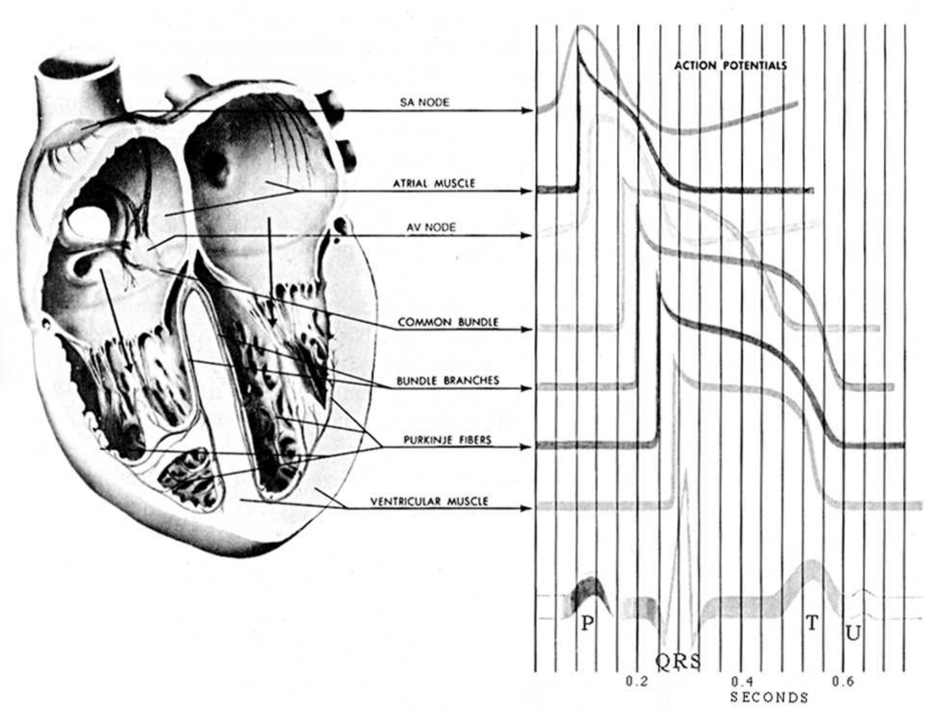

Figure 3.1: The heart and the electrocardiogram. (source unknown)

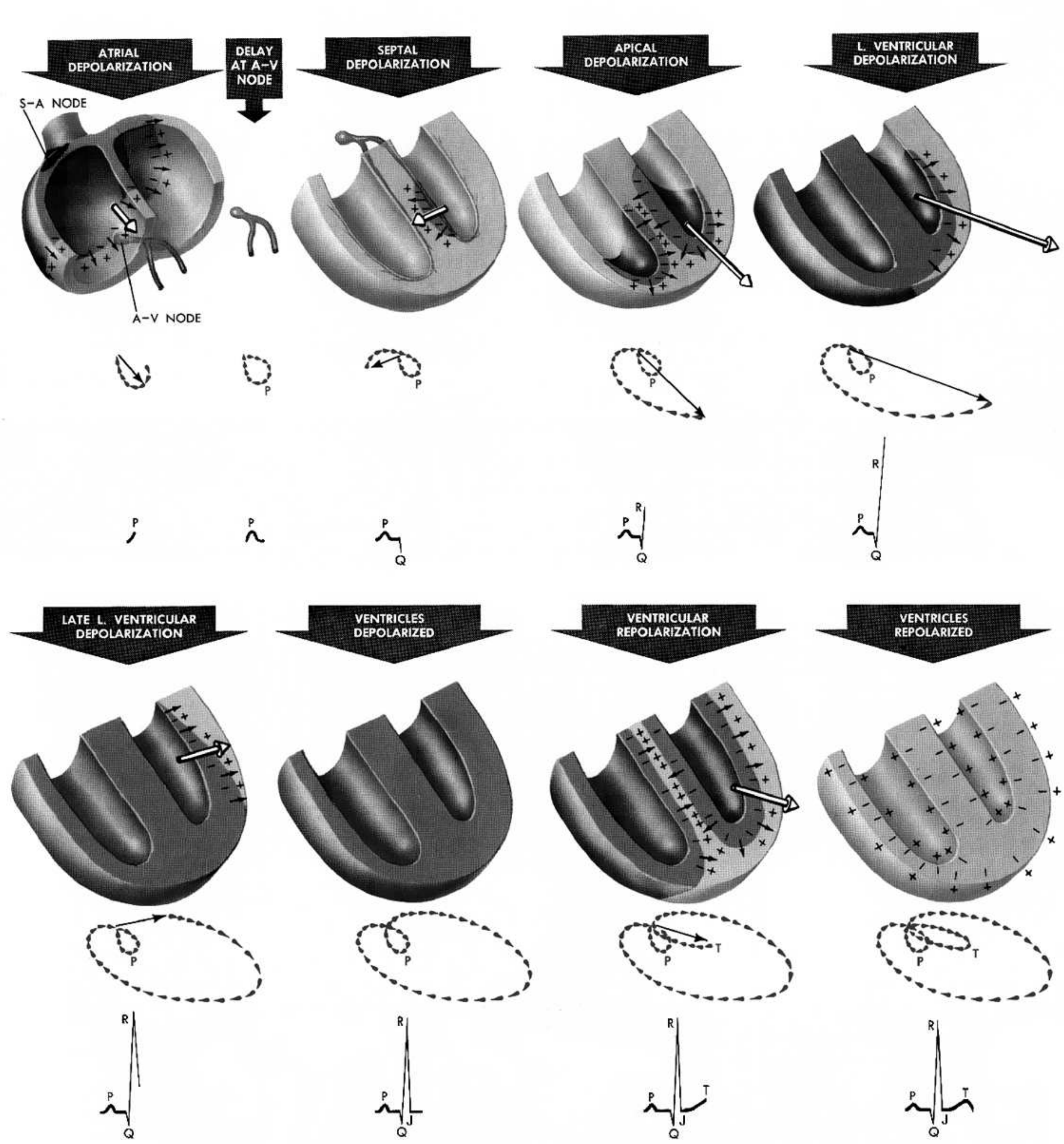

Figure 3.2: The heart, the electrocardiogram and the vectorcardiogram.(source unknown)

and the VCG. Represented as a function of time, the scalar signals are called electrocardiograms (ECG), figure (3.1) and (3.2).

The first electrocardiogram was obtained in 1889 by A. Waller. The technique was further developed by Einthoven, who chose to measure the heart activity as potential differences between the right arm, the left arm and the left leg. Einthoven classified the complex into P-, QRS- and T-waves, where the P-wave is the depolarization of the atria, the QRS-wave is the depolarization of the ventricles and the T-wave is the repolarization of the ventricles.

Around 1904 Einthoven et al. derived the cardiac vector. Measuring three signals and drawing them into "Einthovens triangle" gives an approximate direction of the vector. Hubert Mann described, with the help of Einthovens signals, the change of length and direction of the cardiac vector as a function of time. This procedure takes long time and was therefore not adopted until the 1930:ies, when it became possible to present the obtained loops on an oscilloscope.

To get an accurate picture of the cardiac vector, it was necessary to use a system of measuring the ECG which gave orthonormal coordinates. One problem was that the potentials were measured relative to each other. First of all, potentials had to be measured relative to a common ground. But this still did not give a correct result since the body's electrical resistance had not been taken into account [Arvill; Webster, 1992; Jern, 1987; Pahlm, 1994].

Frank [Frank, 1953,-55], among others, looked for a solution to this problem by performing experiments on a torso model. The model was created of a homogeneous conducting medium, which can be considered a simplification of the human body. Frank came to a solution by measuring the potentials on the surface of the torso model containing a known dipole, and correcting the signals by introducing electrical corrections (like adding resistors between electrodes) and increasing the number of electrodes (leads). These corrections are related to the shape of the torso, the variability of the dipole location and the anatomic variation of the orientation of the heart [Frank 1956]. One of the major problems with Frank's system is that the measurement is very dependent of the placement of the electrodes. Frank's experiments have been compared with experiments on real patients. Humans give fuzzier and wavier lines, which is the result of the simplification made on the torso model. This method is considered to obtain the orthonormal coordinates of the tip of the cardiac vector at each instant. These coordinates are denoted x, y and z, (x is from right to left, y from the head to the feet and z is from the front to the back). Placing all measured points in an orthogonal coordinate system results in a vectorcardiogram.

Scalar electrocardiograms have been used for the past hundred years and are still used today. Since the sixties computers have been used to analyze the ECG and to calculate the VCG. The enthusiasm for the VCG has oscillated a lot during the past 50 years, but the interest has been very large since the beginning of the nineties. [Pahlm, 1994]. Today's medical equipment uses the VCG for calculations and storage, but present the 12 lead ECGs (which are derived from the VCG). The reason why ECGs still are popular is that they are easy to present and doctors are trained to interpret them. Today's medical equipment usually does not show the VCG loops because there is no good way of presenting them. In some systems, VCG loops are presented as projections in different planes (x-y plane, x-z plane and y-z plane—the projection seen from the side, from the front and from above).

These pictures demand a lot from the doctor, who needs a great deal of spatial imagination to understand what the loop looks like.

As an aid to enable the interpretation of the ECG and VCG, certain parameters are calculated from them and displayed as functions of time. Most of these parameters are derived by comparison with the first loop measured on the patient - *the reference loop*. Therefore they describe specific changes of the loop. Other parameters are absolute and describe the current loop.

A study was made [Dellborg, 1991] to investigate vectorcardiography as a method for monitoring acute myocardial ischemia (lack of oxygen in the heart muscle) and came to the conclusion that the VCG has a great advantage of being able to collect information about all changes of the QRS complex in a single parameter. Dellborg also found that dynamic VCG is a user-friendly clinical tool and a good tool for studying ischemic heart disease in man. At the present moment though, it is difficult to say if VCG provides a better diagnosis than ECG. It is more probable that optimal performance can be obtained by combining VCG and scalar ECG (each method presenting information neglected by the other).

Chapter 4

Equipment

My equipment consisted of a computer with Windows NT as operating system. I used visual C++ for Windows NT, since Visual C++ contains a library of graphical functions called OpenGL and since Ortivus already owned it when I started. In OpenGL it is possible to create graphical objects, with different kinds of reflection coefficients. These can be lighted by several light sources. Using the library and including the correct files was sufficiently easy after some trial and error work.

The sample data I used was genuine patient data collected by MIDA. Matrices seemed to be appropriate for storing loop information during calculations, since loop data consists of triplets of coordinates (x, y and z).

To be able to handle the loop data and to be able to perform calculations on it, I installed a mathematical library (Rogue Wave Math Library). This library contains matrices, matrix operations, trigonometric functions etc. Installing this library turned out to be complicated. After two weeks of Sherlock Holmes-like detective work and after removing the random number functions, the library became installable.

Chapter 5

Graphical Presentation

One idea was to create a three-dimensional, beautifully colorful, schematic and rotatable picture of the heart on the screen. Ischemic areas and VCG loops were to be drawn in this heart. In this way, we would obtain an easy to understand picture of the heart's electrical functions. Hearts differ from person to person, depending on the body structure, the amount of bodily fat etc. Also, the heart is not completely fixed inside the body. This makes it difficult to present a correct picture of the heart and its position in the body.

Another alternative was to present the VCG loops and ischemic areas in a bull's eye diagram. The bull's eye diagram is a simple way of presenting a heart in two dimensions. One defines the principal axis of the heart as parallel to and passing through, the left ventricle, figure (5.1). The heart is then divided into slices perpendicular to the principal axis. The slices, which look like doughnuts, are mapped onto a plane one outside another, starting at the apex (the lowest tip of the heart) and upwards, figure (5.2). With appropriate scaling of the different segments, the picture gets realistic proportions.

The bull's eye diagram is often used to present the picture of blood flow through the heart. The necessary information to create a bull's eye diagram can not be deduced from only ECG or VCG. This information is usually obtained by scintigraphy. It is a method of detecting and locating radioactive nuclei, which have been injected into the patients blood steam.

A complicating factor with both presentation methods, is to define where the cardiac vector has its geographical (bodily) origin. It is placed somewhere within the heart and it moves around. The placement alone is not interesting, but is a necessary knowledge if we are to present the loops in a heart or in a bull's eye diagram.

It does not seem possible to pursue these ideas to satisfactory results; even if it is fully possible to draw the pictures, they would not be accurate enough for clinical use and acceptance among doctors.

The simplest way to present the vectorcardiographic loop is to present it in a Cartesian coordinate system, with traditional axis notation (X right- left, Y head-feet, Z front-back). This coordinate system should be easily rotatable around the different axes. To enable the understanding, interpretation and location of the loops, a drawing of a person should be presented together with the coordinate system. This drawing should follow the rotations of the coordinate system. In this way the presentation gives a clear picture of the loops without

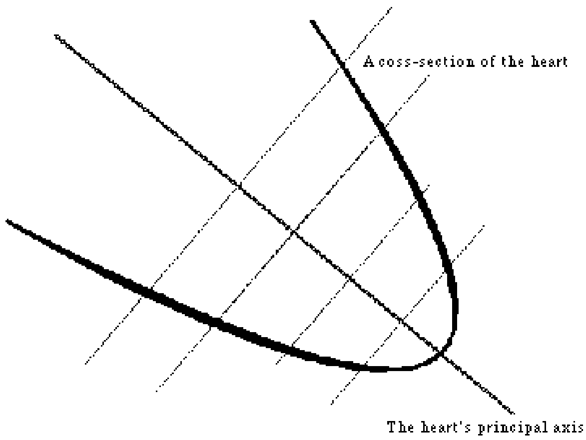

Figure 5.1: The heart seen from the side, sliced perpendicular to the heart's principal axis.

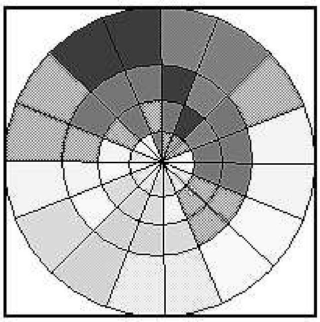

Figure 5.2: Bull's eye diagram, the different shades represent different blood flow

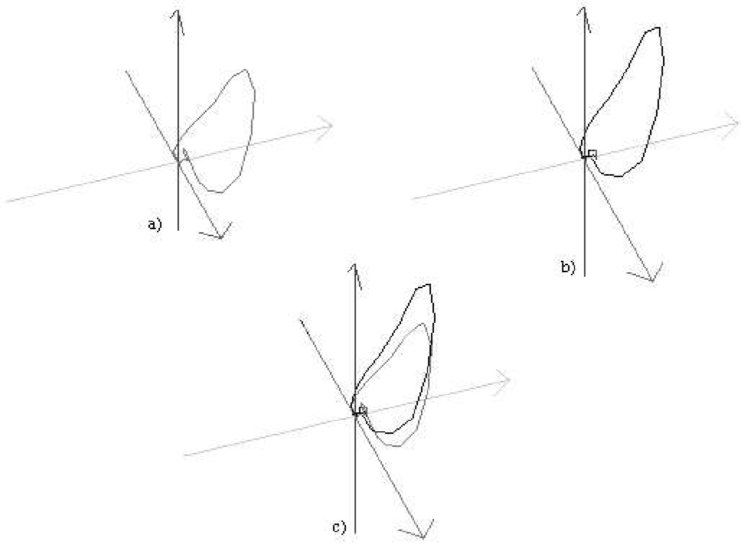

Figure 5.3: a)The reference loop. b)Another loop from the same patient. c)Both loops in the same coordinate system.

visual disturbances, and a clear connection to the body without a need to specify the origin of the system.

The drawing I made was a Cartesian coordinate system with the different axes in different colors; x-blue, y-red and z-green. This is to make it easier to distinguish between different directions also during rotation. The VCG loop is drawn into the coordinate system as a collection of points connected by straight lines. I chose to connect the points by straight lines since the time between two measuring points is very small. In this way loops measured at different times, and different parts of these loops, can be drawn. Many loops can be drawn into the same coordinate system. I chose to give the reference loop a different color to elucidate it, since all the other loops are compared with it, figure (5.3).

The whole picture is illuminated from the front. This gives the loops a slight shading when turned away from the user and brings out the loops' third dimension.

I made the picture rotatable with a step of 10 degrees around the different axes, figure (5.4). The step may seem very large, but the computer used is not capable of rotating the picture very fast and therefore I chose an angle big enough to give the rotation some speed.

To produce all these pictures in a simple way, I used openGL functions. They are fully applicable to pictures as simple as these, but may give problems when producing more complicated objects.

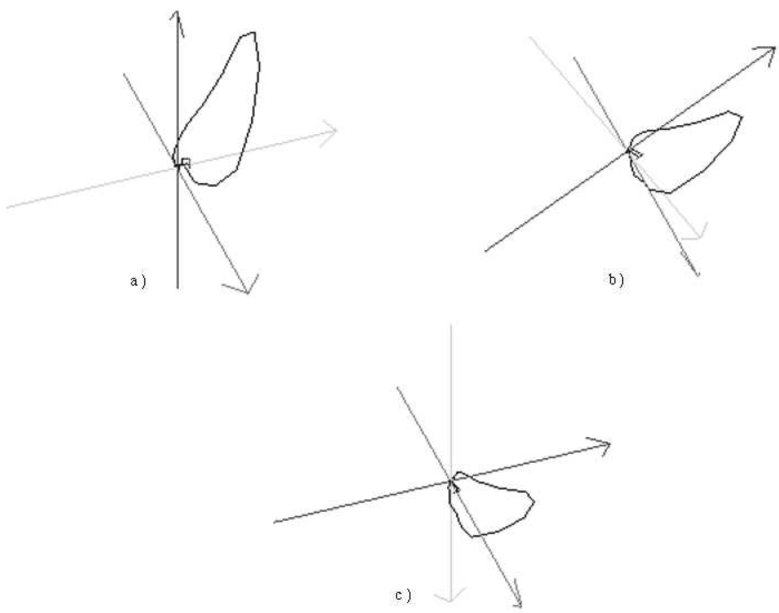

Figure 5.4: Three pictures of a loop seen from different angles.

Chapter 6

Normalization of the VCG Loops

When patients breathe and move around in bed, the VCG and the ECG change. Rolling over to your left side will cause your heart to move so that it comes closer to some of the electrodes. This enlarges and rotates the loop. Such changes are difficult to distinguish from heart malfunction and therefore they disturb the interpretation of the VCG and the ECG.

One hypothesis is that if the loops are moved back to some origin and scaled to some unit size, the artifacts will be eliminated, but the significant features will remain. The transformations performed on the loop will be called the normalization of the loop. I normalize every complex except the reference complex, which I use as unit complex, into which all other loops are matched. The normalization is meaningful when performed on the separate loop segments of a complex (the P-,QRS-, or T-loop). I perform the normalization on the QRS-loop and on the T-loop. Calculations are performed on 75% of the QRS-, or T-loop, but the whole loop is normalized. The last 25% of the loop change a lot from heart beat to heart beat during heart malfunction, and should not be used for normalization.

The different steps of the normalization are displayed in the graphical presentation of the VCG loops, figure (6.2).

6.1 The CAVIAR Method

Fayn, Rubel and Arnaud [Fayn et al 1983] developed a method of normalizing the VCG loops called the CAVIAR method.

According to this method, the set of measurement points that describes the loop is treated as a system of physical points with suitably defined masses. Such a system of points has a mass center and principal axes of inertia.

The first step is to place the loops so that their mass centers and corresponding axes of inertia coincide. According to the authors, this should partially free the loops from extracardiac factors such as thorax anatomy, electrode positioning, respiratory phase, and heart position.

After the loops have been placed in this way, one defines the measure of difference between them as:

$$Mean\ Quadratic\ Deviation = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \|\vec{p_k^i p_k^j}\|^2} \tag{6.1}$$

where N is the number of points, and $\|\vec{p_k^i p_k^j}\|$ is the geometrical distance between the i-th points in the loops. The next step of the normalization consists of translation, rotation and scaling. This is based on the hypothesis that these three kinds of transformation are produced by extracardiac factors.

One must also take into account the fact that identically numbered points in the two loops do not necessarily correspond to the same instants of the heart cycle. The normalization involves thus a fourth transformation: synchronization of the loops by a cyclical shift of points.

The four transformations are applied iteratively. At each iteration, the amount of translation, rotation, scaling or cyclic shift is computed using derivatives.

The minimized MQD is a good measure of the difference between the two loops. It is comparable to other MQDs obtained in the same way.

6.2 My Method

Originally I intended to implement the CAVIAR method for normalizing MIDA loops. But gradually, I discovered some modifications and improvements.

One such modification comes from the observation that parallel translation of a loop distorts the absolute and relative values of measured signals. For example, a point at the origin of the coordinate system represents a zero signal. When it is moved to a distance 10 from the origin, it represents a non-zero signal of 10 units.

Another modification is that I do not perform any synchronization. The points obtained by MIDA are already sufficiently synchronized, so there is no need for a cyclic shift.

Finally, optimal rotation and scaling can be computed in one single step, which eliminates the need of iteration.

As a result of these observations, I decided to use the following method: define the mass center of the loop in the same way as in CAVIAR. Then, define the principal plane of the loop to be the plane passing through the mass center and closest to all points of the loop, in the sense that it minimizes the sum of squared distances to all points.

Rotate the loops around the origin of the coordinate system, so that their principal planes become parallel. Then minimize the difference (equation 6.1) between the loops by rotation within the principal plane and by scaling.

6.3 Finding the Mass Center

Following the CAVIAR method, the measurement points are treated as physical points. Each point is assigned a mass proportional to the speed at which the loop is traced at this point. Since the measurements are made at equal time intervals, this means the mass is proportional to the distance from the neighboring points.

Figure 6.1: a)Original loops. b)Loops with parallel principal planes.

Let the coordinates of the i-th point be $(x_i,\ y_i,\ z_i)$ and let its mass be m_i. The x coordinate of the mass center is obtained from the well-known formula:

$$X_{mass\ center} = \frac{\sum_i m_i x_i}{\sum_i m_i}, \tag{6.2}$$

where the sums are from 1 to N. The formulas for y and z coordinates are analogous.

6.4 Finding the Principal Plane

Given the coordinates of the mass center, the principal plane will be fully determined if I find the vector normal to the plane. To find this vector, I temporarily shift the coordinate system so that its origin is in the mass center. That means, I subtract coordinates of the mass center from the coordinates of all points. All coordinates in this section are coordinates in this shifted system. (After finding the normal vector, I return to the original coordinates.)

Consider any plane P through the origin. Let $\bar{n} = (n_x, n_y, n_z)$ be a unit vector normal to the plane.

Consider any point p with coordinates (x, y, z). The distance D from p is equal to the projection of the vector (x, y, z) onto $\bar{n}$. Because $\bar{n}$ is a unit vector, we have

$$\frac{\bar{n}^2}{\bar{n}} = 1, \tag{6.3}$$

and the projection is equal to the scalar product

$$D = n_x x + n_y y + n_z z. \tag{6.4}$$

The square of the distance is:

$$D^2 = n_x^2 x^2 + n_y^2 y^2 + n_z^2 z^2 + 2n_x n_y xy + 2n_x n_z xz + 2n_y n_z yz. \tag{6.5}$$

Let the coordinates of the i-th point of the loop be x_i, y_i, z_i. Denote:

$$S_{xx} = \sum x_i^2 \tag{6.6}$$

$$S_{xy} = \sum x_i y_i \tag{6.7}$$
$$S_{xz} = \sum x_i z_i \tag{6.8}$$

(All sums above, and in the rest of the thesis are from 1 to N.) The sum of squared distances for all points in the loop is then:

$$S = \sum D_i^2 = n_x^2 S_{xx} + n_y^2 S_{yy} + n_z^2 S_{zz} + 2n_x n_y S_{xy} + \ldots + 2n_y n_z S_{yz} \tag{6.9}$$

This sum is a function of the vector $\bar{n}$:

$$S = S(\bar{n}) = S(n_x, n_y, n_z). \tag{6.10}$$

I want to find the $\bar{n}$ that minimizes $S(\bar{n})$. It is useful at this point to remark a close relationship between the sum $S(\bar{n})$ and the moments of inertia. A moment of inertia of a physical point with respect to a given axis is equal to the mass of the point times the square of distance from the axis. Consider the axis through the origin in the direction of the vector $\bar{n}$, and the point p discussed above. The square of the distance of p from the axis is

$$R^2 = x^2 + y^2 + z^2 - D^2 \tag{6.11}$$

where D is the distance defined by (6.4). If the mass of p is 1, the moment of inertia is equal to $R^2 \times 1 = R^2$. If each of the points of the loop has mass 1, their total moment of inertia around the axis $\bar{n}$ is

$$J(\bar{n}) = S_{xx} + S_{yy} + S_{zz} - S(\bar{n}) \tag{6.12}$$

It is known that each system of mass points has an axis of maximum inertia and an axis of minimum inertia, and that these two axes form a right angle. Together with a third axis, perpendicular to them, they are known as the principal axes of inertia.

It follows from (6.12) that the function $S(\bar{n})$ has a minimum and a maximum for two perpendicular vectors $\bar{n}$. Moreover, it follows that the direction $\bar{n}$ I am looking for is identical with the axis of maximum inertia of the loop (when all points are taken with equal masses), or in other words, that my principal plane is perpendicular to the axis of maximum inertia.

To find the vector $\bar{n}$ that minimizes $S(\bar{n})$, I use the same mathematical trick that is used to determine the principal axes of inertia.

Consider the surface consisting of end points of vectors $v = \bar{n}/\sqrt{S(\bar{n})}$ starting at the origin, for all possible unit vectors $\bar{n}$. (I assume here that $S(\bar{n}) \neq 0$; this is true unless all points are in one plane. One can consider this special case separately and show that my final result is valid also in this case.)

For a given $\bar{n}$, the tip of $\bar{v}$ has the coordinates $x = n_x/\sqrt{S(\bar{n})}$, $y = n_y/\sqrt{S(\bar{n})}$, $z = n_z/\sqrt{S(\bar{n})}$ From this we have:

$$n_x = x\sqrt{S(\bar{n})},\ n_y = y\sqrt{S(\bar{n})},\ n_z = z\sqrt{S(\bar{n})} \tag{6.13}$$

Substituting these in the expression (6.9) for $S = S(\bar{n})$ gives

$$S = x^2 S S_{xx} + y^2 S S_{yy} + \ldots + 2yz S S_{yz}. \tag{6.14}$$

Dividing both sides by S, we obtain

$$1 = x^2 S_{xx} + y^2 S_{yy} + \ldots + 2yzS_{yz}. \tag{6.15}$$

This equation describes a surface of second degree. The concrete meaning of the formula implies that this surface should be an ellipsoid. The longest axis of this ellipsoid corresponds to the direction $S(\bar{n})$ that we are looking for.

An ellipsoid obtained in a similar way for the moments of inertia is called the ellipsoid of inertia. Its principal axes are the principal axes of inertia. As indicated by (6.12), this ellipsoid has the same principal axes, except that the longest and shortest axes are interchanged.

It is known that by rotating a coordinate system, one can always transform the equation of any second degree surface to the form

$$Ax^2 + By^2 + Cz^2 = 1. \tag{6.16}$$

The main axes then coincide with the coordinate axes and their lengths are $1/\sqrt{A}, 1/\sqrt{B}$ and $1/\sqrt{C}$.

To find the direction $\bar{n}$ that minimizes $S(\bar{n})$, we find the coordinate system that transforms (6.15) into (6.16). The axis of the transformed system that corresponds to the smallest of A, B and C has the required direction. Let the matrix M be defined as

$$M = \begin{pmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{xy} & S_{yy} & S_{yz} \\ S_{xz} & S_{yz} & S_{zz} \end{pmatrix}. \tag{6.17}$$

This is also known as the matrix of inertia. Using this matrix, one can write the equation (6.15) as:

$$\begin{pmatrix} x & y & z \end{pmatrix} \mathbf{M} \begin{pmatrix} x \\ y \\ z \end{pmatrix} = 1. \tag{6.18}$$

The rotation of a coordinate system can be expressed as multiplication of coordinates by an orthonormal matrix $\mathbf{T}$. Note that for an orthonormal $\mathbf{T}$, $\mathbf{T}^{-1} = \mathbf{T}^T$. Let u, v, w be coordinates in the rotated system. We then have

$$\begin{pmatrix} x & y & z \end{pmatrix} = \begin{pmatrix} u & v & w \end{pmatrix} \mathbf{T}^{-1}, \quad \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \mathbf{T} \begin{pmatrix} u \\ v \\ w \end{pmatrix}. \tag{6.19}$$

Together with equation (6.15)

$$\begin{pmatrix} u & v & w \end{pmatrix} \mathbf{D} \begin{pmatrix} u \\ v \\ w \end{pmatrix} = 1 \tag{6.20}$$

where $\mathbf{D} = \mathbf{T}^{-1}\mathbf{M}\mathbf{T}$. The equation will have the form of (6.16) if we succeed to choose an orthonormal matrix $\mathbf{T}$ so that $\mathbf{D}$ is a diagonal matrix. Suppose $\mathbf{T}$ is such a matrix. Multiplying both sides of $\mathbf{D} = \mathbf{T}^{-1}\mathbf{M}\mathbf{T}$ by $\mathbf{T}$, we obtain

$$\mathbf{MT} = \mathbf{TD}. \tag{6.21}$$

Written explicitly, this means:

$$\begin{pmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{xy} & S_{yy} & S_{yz} \\ S_{xz} & S_{yz} & S_{zz} \end{pmatrix} \begin{pmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{pmatrix} = \begin{pmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{pmatrix} \begin{pmatrix} d_1 & 0 & 0 \\ 0 & d_2 & 0 \\ 0 & 0 & d_3 \end{pmatrix} \tag{6.22}$$

(we chose **T** so that **D** is diagonal).

Written even more explicitly, this is:

$$\begin{pmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{xy} & S_{yy} & S_{yz} \\ S_{xz} & S_{yz} & S_{zz} \end{pmatrix} \begin{pmatrix} t_{11} \\ t_{21} \\ t_{31} \end{pmatrix} = \begin{pmatrix} t_{11} \\ t_{21} \\ t_{31} \end{pmatrix} d_1, \tag{6.23}$$

$$\begin{pmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{xy} & S_{yy} & S_{yz} \\ S_{xz} & S_{yz} & S_{zz} \end{pmatrix} \begin{pmatrix} t_{12} \\ t_{22} \\ t_{32} \end{pmatrix} = \begin{pmatrix} t_{12} \\ t_{22} \\ t_{32} \end{pmatrix} d_2, \tag{6.24}$$

$$\begin{pmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{xy} & S_{yy} & S_{yz} \\ S_{xz} & S_{yz} & S_{zz} \end{pmatrix} \begin{pmatrix} t_{13} \\ t_{23} \\ t_{33} \end{pmatrix} = \begin{pmatrix} t_{13} \\ t_{23} \\ t_{33} \end{pmatrix} d_3, \tag{6.25}$$

which shows that the three columns of **T** are identical to the eigenvectors of **M**, and the diagonal elements of **D** are the eigenvalues corresponding to them. Because the diagonal elements of **D** are the coefficients A, B, C of (6.16), the direction we are looking for is defined by the eigenvector that corresponds to the lowest eigenvalue. This eigenvalue is equal to $S(\bar{n})$ for this direction.

I chose not to use the least square method, since I am interested in studying the eigenvalues and the eigenvectors. Also, problems can occur with the least square method if the plane is vertical.

6.5 Computing Eigenvalues and Eigenvectors

It follows from the preceding section that to find the principal plane, I need to compute the eigenvalues and eigenvectors of the matrix **M** defined by (6.17).

One possible way is by solving the equation (6.23) for t_{11}, t_{12}, t_{13} and d_1. This boils down to finding λ satisfying the equation

$$\begin{aligned} &Det \begin{bmatrix} S_{xx}-\lambda & S_{xy} & S_{xz} \\ S_{xy} & S_{yy}-\lambda & S_{yz} \\ S_{xz} & S_{yz} & S_{zz}-\lambda \end{bmatrix} = \\ &(S_{xx}-\lambda)[(S_{yy}-\lambda)(S_{zz}-\lambda) - S_{yz}^2] - S_{xy}[S_{xy}(S_{zz}-\lambda) - S_{xz}S_{yz}] \\ &+S_{xz}[S_{xy}S_{yz} - S_{xz}(S_{yy}-\lambda)] = 0. \end{aligned} \tag{6.26}$$

This is a third-degree equation. Its three solutions are the three eigenvalues of **M**. The eigenvectors are then obtained by substituting the eigenvalues, one by one, into (6.23), and solving the resulting systems of linear equations.

This procedure is quite cumbersome. Therefore I chose another method, namely the Jacobi's method described by Fröberg [Fröberg, 1962]. It is an iterative algorithm, but it converges very fast. Its great advantage is that it produces all eigenvalues and all eigenvectors at the same time.

Besides, the resulting eigenvectors are always orthonormal, so we can use them directly to construct the matrix **T** needed to rotate the coordinate system. (The method is applicable only to symmetric matrices; my matrix **M** is by definition symmetric.)

The procedure starts with the matrix **M**, and an identity matrix **V**

$$\mathbf{V} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{6.27}$$

These two matrices are then transformed by a repetitive application of this step:
(Start of iteration)
Identify the non-diagonal element of **M** with maximum absolute value. Let i and k be, respectively, the row and column number of this element.

Compute the angle ϕ,

$$\phi = \frac{1}{2} \arctan \frac{2\mathbf{M}(i,k)}{\mathbf{M}(i,i) - \mathbf{M}(k,k)}. \tag{6.28}$$

Using this angle ϕ, create a matrix **O** with elements

$$\mathbf{O}(\mathbf{i},\mathbf{i}) = \mathbf{O}(\mathbf{k},\mathbf{k}) = \cos(\phi),\ \mathbf{O}(\mathbf{k},\mathbf{i}) = \sin(\phi),\ \mathbf{O}(\mathbf{i},\mathbf{k}) = -\sin(\phi), \tag{6.29}$$

the remaining diagonal element equal to 1, and the remaining elements equal to 0. Using the matrix **O**, transform **M** and **V** as follows:

$$\mathbf{M} = \mathbf{O}^T\mathbf{M}\mathbf{O}, \tag{6.30}$$

$$\mathbf{V} = \mathbf{V}\mathbf{O}. \tag{6.31}$$

The formula (6.28) was so constructed that the elements $\mathbf{M}(i,k)$ and $\mathbf{M}(k,i)$ now are 0. Other non-diagonal elements of **M** that were 0 before the transformation may now be non-zero, but the maximum absolute value of a non-diagonal element is always lower than before the transformation.
(End of iteration step)
A repetition of this step quickly reduces the absolute values of all non-diagonal elements of **M**. When these elements finally become (almost) zero, the diagonal elements of **M** are equal to the eigenvalues of the original matrix, and the columns of **V** are the corresponding eigenvectors. These eigenvectors are always orthonormal.

6.6 Finding the Optimal Rotation

After finding the principal plane of a loop, we return to the original coordinate system, and rotate the loop around the origin so that its principal plane is parallel to the principal plane of the reference loop.

Since we use the matrix **M** of eigenvectors for this purpose, the result of rotation is that not only are the principal planes of the two loops parallel, but also their principal axes of inertia. This, however, is not important, because our next step is rotation in the principal plane to minimize the MQD.

In order to perform the rotation, we temporarily rotate the coordinate system so that the x and y axes are parallel to the principal plane, and the $z-$axis is

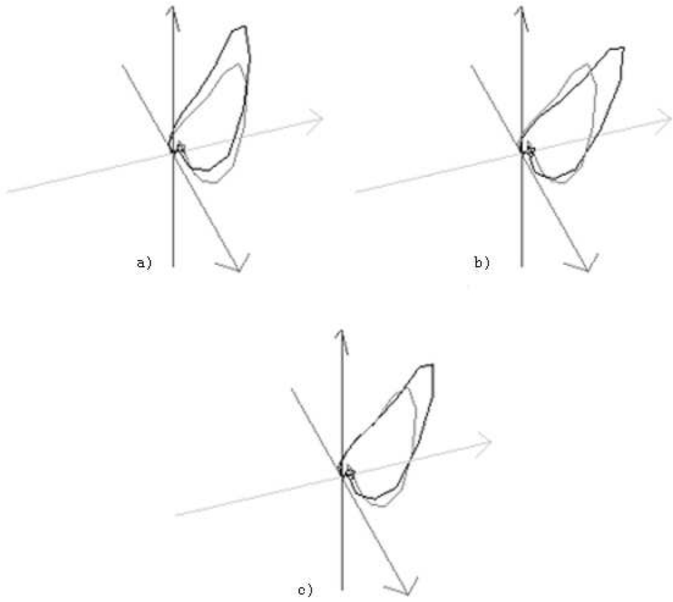

Figure 6.2: a)Unprocessed loops. b)Loops with parallel principal planes. c)Loops optimized to fit each other.

normal to it. All coordinates in the present section are understood to be in this temporary system.

Let X_i, Y_i, Z_i denote the coordinates of the i-th point of the reference loop, and x_i, y_i, z_i coordinates of the i-th point of the loop being normalized. Suppose the loop being normalized is rotated by an angle α around the z-axis. The coordinates of the i-th point after the rotation are:

$$\begin{aligned} x'_i &= x_i \cos\alpha - y_i \sin\alpha, \\ y'_i &= x_i \sin\alpha + y_i \cos\alpha, \\ z'_i &= z_i. \end{aligned} \tag{6.32}$$

We want to choose α so that it minimizes the difference (6.1) between the loops. It is the same as minimizing the sum

$$\begin{aligned} D &= \sum ((x_i \cos\alpha - y_i \sin\alpha - X_i)^2 + (y_i \cos\alpha + x_i \sin\alpha - Y_i)^2 + (z_i - Z_i)^2) \\ &= \sum ((x_i^2 \cos^2\alpha + y_i^2 \sin^2\alpha + X_i^2 - 2x_i y_i \sin\alpha\cos\alpha - 2x_i X_i \cos\alpha + 2y_i X_i \sin\alpha) \\ &\quad +(x_i^2 \sin^2\alpha + y_i^2 \cos^2\alpha + Y_i^2 + 2x_i y_i \sin\alpha\cos\alpha - 2y_i Y_i \cos\alpha - 2x_i Y_i \sin\alpha) \\ &\quad +(z_i - Z_i)^2) \\ &= A\sin\alpha - B\cos\alpha + C \end{aligned} \tag{6.33}$$

where

$$A = \sum y_i X_i - \sum x_i Y_i, \tag{6.34}$$

$$B = \sum x_i X_i - \sum y_i Y_i, \tag{6.35}$$

$$C \textit{ does not depend on } \alpha. \tag{6.36}$$

Denote:

$$M = \sqrt{A^2 + B^2}, \tag{6.37}$$

$$\phi = \arctan(B/A). \tag{6.38}$$

It is easy to see that

$$D = M \sin(\alpha - \phi) + C, \tag{6.39}$$

which has its minimum value for $\alpha = \phi - \pi/2$. We rotate the loop through this angle α, which means changing its coordinates according to (6.32). Then we return to the original coordinate system.

6.7 Finding the Optimal Scaling

As a final step, we scale the loop being normalized to minimize the MQD.

Let X_i, Y_i, Z_i denote the coordinates of the i-th point of the reference loop, and x_i, y_i, z_i coordinates of the i-th point of the loop being normalized. Scaling the loop by a factor s means changing its coordinates to:

$$\begin{aligned} x'_i &= s x_i, \\ y'_i &= s y_i, \\ z'_i &= s z_i. \end{aligned} \tag{6.40}$$

I want to choose s such that it minimizes the difference (6.1) between the loops. It is the same as minimizing the sum

$$\begin{aligned} D &= \sum\left((sx_i - X_i)^2 + (sy_i - Y_i)^2 + (sz_i - Z_i)^2\right) \\ &= \sum(s^2x_i^2 + X_i^2 - 2sx_iX_i + s^2y_i^2 + Y_i^2 - 2sy_iY_i + s^2z_i^2 + Z_i^2 - 2sz_iZ_i) \\ &= s^2\sum(x_i^2 + y_i^2 + z_i^2) + \sum(X_i^2 + Y_i^2 + Z_i^2) - 2s(\sum x_iX_i + \sum y_iY_i + \sum z_iZ_i). \end{aligned} \tag{6.41}$$

To obtain the optimal scale factor, compute the derivative:

$$dD/ds = 2s\sum(x_i^2 + y_i^2 + z_i^2) - 2(\sum x_iX_i + \sum y_iY_i + \sum z_iZ_i). \tag{6.42}$$

This becomes 0 for

$$s = \frac{\sum x_iX_i + \sum y_iY_i + \sum z_iZ_i}{\sum(x_i^2 + y_i^2 + z_i^2)}. \tag{6.43}$$

This value of s must correspond to a minimum of D (the second derivative is obviously positive). Notice that scaling does not change the direction of the principal plane, so the principal planes remain parallel after scaling. Also, it does not change the ratio B/A used in (6.38) to compute the optimal rotation. That means, the loop remains optimally rotated even after the scaling.

Chapter 7

Old and New Diagnostic Parameters

After normalizing a loop, the MIDA files are changed to contain newly calculated parameters based on the normalized loops. To be able to compare old parameters calculated on normalized loops, we also save the old parameters calculated on the original loops. The parameters consist both of those commonly used and those invented by me. Hopefully they contain the most relevant pieces of information about the loop. All parameters are calculated for all loops, so that trends can be studied.

The names of these parameters are intentionally short, since they are to be studied with help of MIDA, which only allows eight characters.

7.1 Old Diagnostic Parameters

The abbreviation *us* means all rotations but no scaling and is short for no scaling, *utan skalning* in Swedish, while *ms* means all rotations and scaling, *med skalning.*

7.1.1 X-ST, Y-ST, Z-ST original, us and ms

X-ST, Y-ST and Z-ST are coordinates of the point 60 ms after the J-point (the point where the QRS-loop ends) in a VCG loop. The original coordinates and the coordinates before and after scaling are saved.

7.1.2 ST-VM ms

ST-VM is the *ST Vector Magnitude.* It is the length of the vector from the origin to the ST point in a complex (60 ms after the J-point), figure (7.1). Calculating ST-VM after only rotations will give the same result as if calculated without any rotation at all. Rotating a loop around the origin does not change the distance between the origin and the loop.

$$ST - VM = \sqrt{ST_x^2 + ST_y^2 + ST_z^2} \tag{7.1}$$

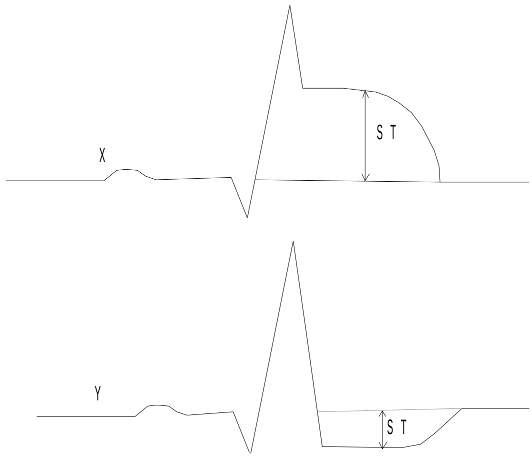

Figure 7.1: ST-VM in the x and y direction

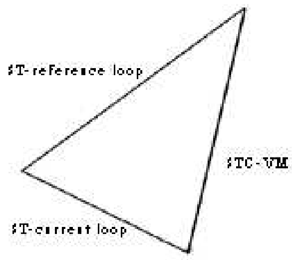

Figure 7.2: STC-VM

ST-VM reflects ischemia during infarction and gives information about its location.

7.1.3 STC-VM us and ms

STC-VM is the *ST Vector Magnitude Change.* It is a measure of the change of ST-VM compared with the reference loop, and is calculated as the length of the vector between the current ST-vector and the ST-vector of the reference loop, figure (7.2).

$$STC - VM = \sqrt{(ST_{rx} - ST_{cx})^2 + (ST_{ry} - ST_{cy})^2 + (ST_{rz} - ST_{cz})^2} \quad (7.2)$$

where ST_r is the ST-point in the reference loop ST_c is the ST-point in the current loop.

This parameter reflects myocardial ischemia.

7.1.4 QRS-VD us and ms

This is QRS Vector Difference, and is a relative parameter since it involves comparison with the reference complex. The difference in area is taken between

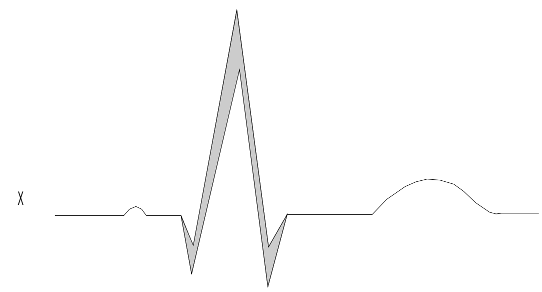

Figure 7.3: The difference in the x-direction

the two complexes, figure (7.3), in three different projections x, y and z.

QRS-VD is calculated as the sum of areas:

$$QRS - VD = \sqrt{A_x^2 + A_y^2 + A_z^2} \tag{7.3}$$

QRS-VD reflects both ischemia and necrosis.

7.2 New Diagnostic Parameters

The new diagnostic parameters are supposed to contain the information about the VCG complex which is omitted by the old parameters. The parameters should contain information about how the loop has changed in comparison with the reference loop. Some parameters should reflect the forms of the different parts of the complex, since there is little known about these changes during heart malfunction. Most of the parameters are calculated on the QRS-loop, since that part of the VCG complex was considered the most interesting at the persent time. The parameters may as well be calculated for the P-loop or the T-loop.

Uopt means without optimization and *mopt* means with optimization, where optimization is all alterations of the form and placement of the loop after making the prefered planes parallel.

7.2.1 PlanVink

This angle between the current loop's principal plane and the reference QRS-loop's principal plane. It is calculated as the angle α between the planes' normal vectors

$$\bar{a} \times \bar{b} = |\bar{a}||\bar{b}| \cos \alpha. \tag{7.4}$$

7.2.2 Rotation Angle - RotVink

The rotation angle is the angle the current loop must be rotated relative the reference QRS-loop, to minimize the mean quadratic deviation. This rotation is performed after making the principal planes parallel, and is a rotation around the origin.

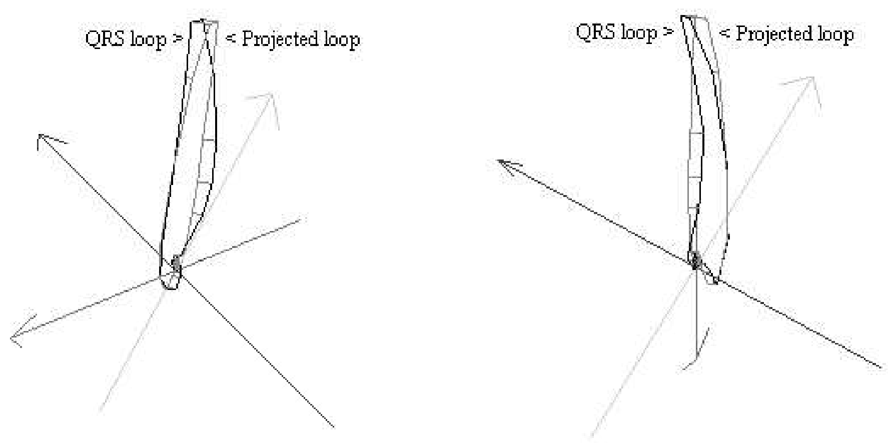

Figure 7.4: A loop and its projection on the plane seen from two different angles.

7.2.3 Scaling Factor - ScalFact

The scaling factor is the factor with which all points in the loop are multiplied to minimize the quadratic distance between the loop and the reference loop.

7.2.4 MQD uopt and mopts

MQD stands for Mean Quadratic Deviation and is the sum of quadratic distances between corresponding points in the current loop and in the reference QRS-loop.

$$MQD = \sum (M_{Ci_x} - M_{Ri_x})^2 + (M_{Ci_y} - M_{Ri_y})^2 + (M_{Ci_z} - M_{Ri_z})^2 \qquad (7.5)$$

It is a measure of the form difference between the two loops.

7.2.5 The Bulginess of the Loop - AvPlan

This is a measure of how curved, or bulging the loop is. It is defined as the square root of the quadratic distance between the points in the loop and their projection on the principal plane, figure(7.4). The parameter is normated with the number of measuring points.

To find the point's projection, a plane can be defined as

$$Ax + By + C = z. \qquad (7.6)$$

All points x, y and z that fulfill the equation are points on the plane. Let x_0, y_0, z_0 be a point on the plane. $Ax_0 + By_0 + C = z_0$ must therefore be true. Create the vector $\bar{v}$ as a vector on the plane from x, y, z to x_0, y_0, z_0, $\bar{v} = (x - x_0, y - y_0, z - z_0)$. Now let $\bar{n} = (n_x, n_y, n_z)$ be the normal to the plane. Since $\bar{n}$ and $\bar{v}$ are perpendicular, their scalar product should be equal to zero.

$$\bar{n} \times \bar{v} = 0, \tag{7.7}$$

$$n_x(x - x_0) + n_y(y - y_0) + n_z(z - z_0) = 0. \tag{7.8}$$

Rewritten

$$\frac{n_x x}{n_z} + \frac{n_y y}{n_z} - (\frac{n_x x_0 + n_y y_0 + n_z z_0}{n_z}) = z. \tag{7.9}$$

Identification with equation (7.6) gives:

$$\begin{aligned} A = &\quad \tfrac{n_x}{n_z} & (7.10) \\ B = &\quad \tfrac{n_y}{n_z} & (7.11) \\ C = &\quad -(\tfrac{n_x x_0 + n_y y_0 + n_z z_0}{n_z}). & (7.12) \end{aligned}$$

The normal vector can now be written as $\bar{n} = (A, B, 1)$

Projecting the loop on it's principal plane means projecting each measuring point P_i onto the plane. This means finding a point on the plane p_i such that the vector between P_i and p_i is perpendicular to the plane. Let this vector be $Q\bar{n}$, where Q is a scalar. Each measuring point in the loop consist of three coordinates x, y and z. Let us denote a measuring point P_x, P_y, P_z. I now have

$$(P_x, P_y, P_z) - Q\bar{n} = (p_{xi}, p_{yi}, p_{zi}). \tag{7.13}$$

Equation (7.13) can be written as:

$$\begin{aligned} p_{xi} &= P_x - QA & (7.14) \\ p_{yi} &= P_y - QB & (7.15) \\ p_{zi} &= P_z - Q. & (7.16) \end{aligned}$$

$Ap_{xi} + Bp_{yi} + C = p_{zi}$ together with (7.16) will give

$$Q = \frac{AP_x + BP_y + C}{P_z + A^2 + B^2} \tag{7.17}$$

We can find the coordinates of the points projection on the principal plane.

7.2.6 Length of the Loop Divided by the Area - SL/Area

The length of the loop divided by its enclosed area is a measure of the geometrical form of the loop. The smallest value possible occurs when the loop has the form of a circle, the length of the loop is minimal and the area maximal.

The length of the loop, which I call the sling length, is calculated by adding the distances between consecutive points together. The distance D is:

$$D = \sqrt{(X_i - X_{i+1})^2 + (Y_i - Y_{i+1})^2 - (Z_i - Z_{i+1})^2} \tag{7.18}$$

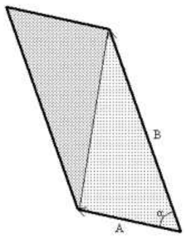

Figure 7.5: The area calculated by $|\vec{A} \times \vec{B}|$

The area of the loop is more complicated to calculate. Assume two vectors $\vec{A}$ and $\vec{B}$. The result of their crossproduct $\vec{A} \times \vec{B}$ is a vector perpendicular to both $\vec{A}$ and $\vec{B}$ which I choose to call $\vec{C}$. The absolute value of $\vec{C}$ is two times the area spanned by the vectors $\vec{A}$ and $\vec{B}$, figure (7.5). Calculating the area for the whole loop means calculating each separate area between vectors pointing from point 1 to point $i + 1$ and $i + 2$, where $i = 1 \ldots N - 2$ for a loop containing N points.

7.2.7 Quotient of Eigenvalues

The lowest eigenvalue gives the eigenvector perpendicular to the principal plane. The other two eigenvalues give eigenvectors perpendicular to the first eigenvector. These are also perpendicular to each other, and lie in the principal plane. The quotient of the two highest eigenvalues gives a measure of the symmetry and the form of the loop.

An illustration, consider this example: for a circle and a square, both symmetric figures, the two highest eigenvalues are equal. Their quotient is 1. An ellipse has eigenvalues proportional to the squares of the ellipse's major and minor axes. Badilini et al. have studied the form of the T-loop, by introducing a parameter of planarity PL based on the eigenvalues $\lambda_1, \lambda_2, \lambda_3$ with $\lambda_1 > \lambda_2 > \lambda_3$ calculated from the inertia matrix.

$$PL = 100 - \frac{100\lambda_3}{\lambda_1 + \lambda_2 + \lambda_3} \tag{7.19}$$

PL is expressed in percent and is a measure of the importance of the smallest eigenvalue with respect to the other two. For a loop lying in the principal plane $PL = 100$. The research team found that changes in PL were very small i.e. the planarity of the T-Loop did not change much, not even in extreme cases. The value of PL was around 90 here, which tells us that the majority of the loop was lying in the principal plane.

Chapter 8

Ischemia

Ischemia is lack of oxygen. Myocardial ischemia is lack of oxygen in the heart muscle, usually caused by lack of blood flow in the coronary arteries. We want a method to localize the exact position of the blocked artery. We also would like to localize the ischemic area, it's size and severeness. Several studies have been made on different aspects concerning ischemia.

One of these studies [Näslund, 1992] is on the development of reliable diagnostic methods of myocardial ischemia. Experiments were performed on pigs, where a ball was inserted into a coronary artery to produce occlusion, and retracted to produce reperfusion. The absolute parameters did only show a faint sensitivity for ischemia. The most interesting parameter was the QRS-vector direction and magnitude. Its changes are directed towards the ischemic area. The relative parameters (parameters that include comparison with the reference complex) increased after occlusion and decreased after reperfusion, but gave large peaks in connection with reperfusion. Since the relative parameters react to occlusion, they may be of clinical use to determine the size and location of the ischemic area. They are calculated, as I have said earlier, relative to the reference complex, which in this experiment was a healthy complex. But patients are normally monitored some time after occlusion. The reference complex is not healthy, and the relative parameters do not reflect what is happening the same way it did in the experiments.

However, another study [Steg, 1995] indicates that the ST-segment changes can not say anything about the myocardial area at risk during myocardial ischemia. Steg's conclusion is that ST-changes give information about the severity of the ischemia instead of the extension.

It does not seem possible to localize ischemia accurately enough, with the help of electrical information only. It is also impossible to present ischemia in a bull's eye diagram or in a picture of a heart without knowing anything about the hearts geometry. Therefore, we chose not to present the location of ischemia.

Chapter 9

Results and Discussion

9.1 Problems Connected with the Calculations

The method of making planes parallel described and applied here is very accurate and functionable in cases where the loops have a healthy or kind form. This is valid for a majority of the patients I have studied. But problems arise when this method is applied on more distorted loops. The mapping is performed using the eigenvectors as described earlier. So the main problem is to find the correct set of eigenvectors. These are calculated from the inertia matrix, based on the measuring points. The matrix does not reflect the order of the points. The system of eigenvectors we obtain is a right-handed system of orthonormal vectors, but there is no guarantee that the normal vector is pointing in the medically correct direction. An incorrect direction produces a "mirror reflection". How should the correct direction be defined? I did not succeed in isolating the cases where the normal vector points in the incorrect direction. Just looking at the tracing direction will not help since sick loops may start by moving in the wrong direction. One solution may be to compare the reference loop with the current loop. Another way may also be some kind of comparison among loops, to reveal if any mirror reflection has taken place. A mirror reflection will in most cases give large differences between the loops being compared and therefore make the calculated parameters large. A reflection can, in some cases, give lower values than expected since it fits the reference loop better than it should. I believe that important information would be lost in these cases.

9.2 Clinical Evaluation

9.2.1 The Material

The old and new parameters where calculated on QRS-loops from five MIDA files. Two of these files are from patients with infarction, one file is from a patient with instable angina (a heart condition) and two files are from undiagnosed patients with documented position changes.

In one of the files the rotational angle (RotVink) alternates between $+40$ and -140 degrees. This may be caused by a normal vector pointing in the medically wrong direction in some of the loops. This does not seem to alter the other parameters.

9.2.2 Comments to the Parameters

ST-VMms is equal to ST-VM times the scaling factor. The parameter becomes a parameter relative to the reference loop since the scaling factor depends on the size of the reference loop.

QRS-VDms seems to almost eliminate changes in position. The difference between QRS-VD and QRS-VDms changes depending on the patient. The two infarct patients show very large differences.

PlanVink is very small and does not vary much more than one degree. During severe ischemic episodes the parameter changed more. Maximum value 6 deg.

RotVink varies up to 25 degrees and changes when the patient lies on the left side.

SkalFact changes in the range between 0.5 and 1.2. It seems to be the main reason why QRS-VDms is smaller than QRS-VD, and why position changes do not show.

AvPlan is very dependent on where the ischemia is.

SL/YTA is difficult to connect with anything specific.

9.2.3 The Results of the Study

Today there are several ways of detecting ischemic episodes and of determining the size of the ischemic area.

Ischemic episodes are detected by changes in ST-VM or in STC-VM. QRS-VD shows high sensitivity to ischemia, but is not specific enough. Hopefully QRS-VDms and ST-VMms can be used to detect ischemic episodes.

ST-VM shows whether reperfusion has been successful or not.

Today, an estimation of the infarcted size is made from QRS-VD and ST-VM. The correlation between the calculated size and the parameters is very low. Maybe the normalized QRS-VDms or one of the absolute parameters will give a better estimation.

9.3 Further Improvements

Other improvements, apart from the ones described in this thesis, may be to increase the number of options in the graphical section. The user should be given the opportunity to look at and normalize different parts of the loop.

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