"AN EVALUATION OF PLANARITY OF THE SPATIAL QRS LOOP BY THREE DIMENSIONAL VECTORCARDIOGRAPHY: ITS EMERGENCE AND LOSS"

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Abstract

Aims

To objectively characterize and mathematically justify the observation that vectorcardiographic QRS loops in normal individuals are more planar than those from patients with ST elevation myocardial infarction (STEMI).

Methods

Vectorcardiograms (VCG) were constructed from three simultaneously recorded quasi-orthogonal leads, I, aVF and V_2 (sampled at 1000 samples/sec). The planarity of these QRS loops was determined by fitting a surface to each loop. Goodness of fit was expressed in numerical terms.

Results

15 healthy individuals aged 35 – 65 years (73% male) and 15 patients aged 45 – 70 years (80% male) with diagnosed acute STEMI were recruited. The spatial-QRS loop was found to lie in a plane in normal controls. In STEMI patients, this planarity was lost. Calculation of goodness of fit supported these visual observations.

Conclusions

The degree of planarity of the VCG loop can differentiate healthy individuals from patients with STEMI. This observation is compatible with our basic understanding of the electrophysiology of the human heart.

Key words:

Vectorcardiogram, QRS plane, uniform double layer, STEMI, healthy controls

Highlights

- Vectorcardiograms were constructed by an easy and relatively accurate method using leads I, aVF and V_2.
- The planarity of the three-dimensional loops was evaluated by 'surface fitting' using the MATLAB platform.
- The spatial QRS loops were found to be essentially planar in normal controls but not in patients with an acute myocardial infarction.
- QRS planarity in normal controls and its loss in acute myocardial infarction can be explained by the uniform double layer theory of the spread of ventricular depolarization.

INTRODUCTION:

Vectorcardiography(VCG) represents the summation of all the instantaneous electrical vectors generated in the heart by myocardial cells and is designed to display the multidirectional view of space-time cardiac electrical activity.

The VCG loop contains threedimensional recurring, near-periodic patterns of cardiac dynamics, and may be projected onto three mutually perpendicular planes to capture the time-space interrelations, or plotted as a static attractor in a 3D space that provides the topological relationships (Fig. 1).

The present study is aimed at displaying the VCG by a simple technique to characterize spatial patterns of cardiac electrical activity. Among various features and observations in the present paper, we would like to emphasize an interesting feature, namely the planarity of the 3D-QRS loop in healthy individuals. The striking characteristic of the normal 3D-QRS loop is that it lies approximately in a single ***"plane of predilection"***.

Planarity of Normal QRS VCG spatial loop: There are a number of reports in the literature [1-14] suggesting that the QRS complex of the three-dimensional spatial VCG loop is essentially planar in normal persons.

In 1936, Schellong first reported that, in normal subjects, the spatial QRS loop lies approximately in a single plane [1]. Rochet and Vastesaeger[2] confirmed andextended this observation, reporting the variations of normality. Milnor [3]introduced quantitative expression to the QRS plane by means of the panoramic vectorcardiogram. Frank (1956) also observed that normal vectorcardiographic loops are found to lie essentially in a plane, the ratio of maximum length to maximum width-viewed-edgewise usually being at least 10:1 in normal persons [4].

Seiden[5]also confirmed Milnor's and Frank's observations of the planarity of loops, and Howitt and Lawrie[6]called for an explanation of this phenomenon in terms of the spread of depolarization in the heart.

Rochet and Vastesaeger[2] identified the QRS plane of predilection and departures from it. They defined this as the plane in which the ratio of major/minor amplitude is smallest. Accordingly, this QRS plane (Schellong's"*plane of the QRS loop"*,Rochet and Vastesaeger's"*plane of predilection*") is supposed to be a normal finding and provides a useful standard of reference for defining the normal VCG.

Significance and evaluation of the QRS Plane

As Milnor pointed out[3], the fact that the normal spatial QRS loop lies approximately in a single plane is rather surprising. When the complex structure of the ventricular musculature is considered together with the numerous possible pathways along which the depolarization impulse passes, it is a rather striking observation that the termini of the successive instantaneous vectors should lie in a single plane.

In the following years, planarity evaluation was done utilizing a number of geometrical procedures. The conventional orthogonal reference frame of VCG (Frank's lead) was normalized to patient's own horizontal frame, through controlled rotation by exchange of axes of coordinates using customized resolver. The QRS planarity was subsequently calculated by measuring length, width, thickness, and ratios of width/length and thickness/length of the QRS loop in edgewise and broadside projections [7]; or calculated from the percentage ratio of the peak-to-peak deflection in the Y lead to that in the X lead axes of the transformed frontal plane – *Non-planarity index*[8]. The planarity of the QRS loop was also assessed from the degree of deviation of frontal QRS loop after lead axis rotation [9]. Mossard (1984) described a method of calculation of the planes of the vectorcardiographic loops by a coefficient of left-sidedness obtained by the sum of squares of the distances between the points on the loop in the plane, which was then normalised with respect to the size of the loop [10].

However, although the phenomenon of QRS loop planarity was detected some time ago, it has not been regularly investigated and quantitatively analyzed in research and clinical practice. Even a recent review by Man *et al* (2015), has not emphasised this *crucial* issue [11]. This is partly because the multiplicity of methodologies of constructing a 3D-VCG loop and evaluating the planarity status are quite cumbersome, intricate and poorly standardized. With rapid advancements in information technology and the easy availability of computing hardware and software, representation of 3D-VCG loops isnot constrained by computational resources anymore, and that has generated renewed interest in the VCG[11]. A proper evaluation of this issue will not be possible until there is more knowledge about the QRS plane and the relationship between the QRS plane and the pathway of ventricular activation.

In 2015, Tereshchenko *et al* used the standard 12-lead ECG and transformed it into orthogonal XYZ ECG leads using the inverse Dower transformation. They calculated the QRS loop planarity as the mean of the dihedral angles between two consecutive planes for all planes generated for the median beat.[12].

In 2016, Sedaghat *et al [13]* calculated the *planarity index*using the tool “geometrical area vector”, proposed by Pierre Amaud in 1989 [14] . GAV was defined as the resultant vector of normals to the triangles formed by consecutive QRS vectors. The magnitude of each normal vector was set to the area of its corresponding triangle. The planarity index (GAV %) was defined as the ratio of the magnitude of GAV to the area of the entire QRSloop.

The present paper proposes a simple method of constructing the 3D-spatial VCG from the routine clinical ECG, in a resource poor setting and of evaluation of the planarity status of the QRS loop. In other words, the present protocol is designed to obtain the Space-domain VCG signal from the Time-domain ECG signal and extract the possible planarity features with appropriate characteristic equations. We used a standard software tool,with established mathematical and statistical backing,for evaluating the issue of planarity.

The aim was to objectively characterize and mathematically justify the observation that vectorcardiographic QRS loops in normal individuals are more planar than those from patients with ST elevation myocardial infarction.

We also propose and put forward certain possible mechanisms consistent with the present physiological knowledge to explain QRS planarity and its loss in disease states like acute myocardial infarction (AMI).

MATERIAL AND METHODS:

We conducted a descriptive observational study on the extraction of features from the VCG in a group of patients with acute myocardial infarction (AMI) admitted to hospital. After approval of the Institutional Ethics Committee and obtaining informed consent from each of the individual subjects, the study protocol was instituted. 15 healthy individuals aged between 35 and 65 years with a median age of 55 (73% male) and 15 patients with diagnosed ST elevation myocardial infarction (STEMI) aged between 45 and 70 (median age 60, 80% male) were recruited, from whom conventional scalar ECG data were collected at the point of admission, before administration of any therapy. All the patients with AMI were recruited as per pre-determined criteria based on their clinical, electrocardiographic and biochemical profile . Each met ECG criteria for STEMI [15] and was admitted to the hospital from 5 to 24 hours after the onset of symptoms.

Throughout the research work, including clinical workup, data collection, recording, analysis etc., we strictly conformed to the World Medical Association

Declaration of Helsinki regarding the ethical principles for medical research involving human subjects.

Three simultaneous lead ECG signals were obtained by using a digital electrocardiograph (RMS India; sampled at 1000 samples/second). In the absence of traditionally used Frank's orthogonal leads (X, Y, and Z) [4] or a hybrid lead system based on Frank's image space [16] in a resource poor setting, we used leads I, aVF and V_2 as a reasonably close approximation to orthogonal leads.

Hamlin and associates [17,18] used Leads I, aVF and V_{10} as quasi-orthogonal X, Y and Z leads respectively, in an animal model. However, we chose the anteriorly directed V_2 as the Z axis and accordingly selected three conventional leads I, aVF and V_2as having a reasonable approximation to the representative X, Y and Z leads respectively.

It can be mathematically proved by Dower's transformation [19] that a planar structure in the quasi-orthogonal I, aVF and V_2 lead system is preserved in Frank's orthogonal X, Y, Z lead system. The converse is also true, namely that the planarity property in the Frank lead system should remain invariant in our proposed lead system.

In order to test our proposition, we took two sets of data of normal persons from the "PTB Diagnostic ECG Database: Subject Nos. 104, 105" of www.physionet.org [20]. Construction of the spatial QRS loops and planarity assessment as per the proposed "Surface/Plane fitting procedure" were carried out utilizing the Frank's X, Y, Z leads and the proposed quasi-orthogonal leads (I, aVF, V_2). The values of the 'goodness of fit' criteria obtained from both these data-sets indicate that both the loops are planar. The visual inspection of the 'surface fit' also supports this information.

For the sake of brevity, the detailed findings of this validation are provided on-line as supplementary material.

Construction of 3D Spatial VCG: The recorded digitized data of each quasi-orthogonal lead were used to construct the 3D-VCG. Simultaneous time series of the ECG dataset from three mutually perpendicular leads as described were utilized to draw the 3D-VCG loop using MATLAB.We assessed various morphological features of this loop and its 2D planar projections (Fig. 1).

As shown in Fig. 1, the VCG vector loops contain three-dimensional recurring, near-periodic patterns of heart dynamics, which can be visualized in the X, Y, Z space domain. The hidden and implicit temporal variations between cardiac cycles can be visualized in the dynamic recording if required[21]. In our lab, the 3D loopscan be rotated freely on the computer screen enabling loops to be viewed from different angles and analyzed visually.

Determination of the Plane incorporating the QRS Loop:
We fitted a plane z = ax + by + c to the three-dimensional points which constitute the QRS loop. The QRS onset and termination were determined manually and care was taken to exclude the P and T loops from the fitting. The fitting was done by using the surface fitting tool box in MATLAB in order to determine the required plane by projecting the QRS-loop on to the best-adjusted plane computed by least mean squares methods which minimize the distances from the loop points to the calculated plane. The tool finds out the surface clustering of the maximum number of spatial points of a given variable and attempts to make a "fit" to all those surface points in a single optimal plane.

Goodness of Fit statistics
Quantitative evaluation of the planarity of 3D QRS loop was assessed using Goodness of fit criteria. This is a statistical model with the assumptions of least-squares fitting, where the model coefficients can be estimated with the little uncertainty and are easy to interpret. The specific measures studied were as follows:

a) **Sum of Squares Due to Error (SSE)** is the sum of the squares of residuals i.e. the deviations of predicted values from actual empirical values of data. A value closer to 0 indicates that the model has a smaller random error component and that the fit will be more useful for prediction.
Root Mean Square Error (RMSE) is a measure of the difference between point locations that are known and locations that have been interpolated or digitized. It is the root mean squared difference between known and unknown points and estimates the standard deviation of the random component in the data. A value closer to 0 indicates a fit that is more useful for prediction.
b) **R^2**is the coefficient of determination that indicates how well a data set fits a statistical model – sometimes simply a line, a curve or a surface. R-square can take on any value between 0 and 1, with a value closer to 1 indicating that a greater proportion of variance is accounted for by the model.
c) **Adjusted R^2**calculates the proportion of the variation in the dependent variable accounted for by the explanatory variable. The adjusted R-square statistic can take on any value ≤ 1, with a value closer to 1 indicating a better fit.

The detailed mathematical description of these statistics can be found elsewhere[22]. The values of these goodness of fit parameters were compared between cases of STEMI and normal controls using the one-tailed unpaired't' test.

Along with the statistical evaluation of the QRS planarity by the above methodology, we also visually confirmed the QRS planarity. Fig. 2a is the QRS Spatial Loop in 3D Space in a normal control subject (Mr. RK). Each point represents the tip of the instantaneous vector. To test the planarity, a surface/plane was applied in the surface fitting tool box in Matlab platform (Fig. 2b). Then, the whole three-dimensional frame was manually rotated (from Figs. 2c to 2d to 2e),to test whether the surface/plane to "fit" or "overlie" on the given spatial QRS loop, in the best possible way (Fig. 2f).

RESULTS:

The QRS segment of the spatial VCG loop in normal controls exhibits a planar orientation in 3D space, and in general, the end of the QRS loop passes through the origin (0, 0, 0).

The statistical criteria of goodness of surface fit exhibit a low value of SSE and RMSSE and high values for R-Square and Adjusted R-Square, which indicate that the deduced model is a good fit and useful for prediction (Table 1).

Fig. 3 explicitly shows illustrations of the planarity status of the 3D-QRS loop in several normal control subjects. In all of them, the 3D-QRS loop can be satisfactorily fitted with a plane which implies that each is approximately situated in a single plane.

The QRS loops obtained in STEMI cases lost their planarity and the termination of the loop did not pass through the origin. They also did not form a closed loop and in most of this group of patients, remained open.

The statistical criteria of surface goodness of fit also exhibit a very high value of SSE and RMSSE and a low value of R-Square and Adjusted R-Square, which indicate that the model is a poor fit. The comparison table shows that there is a highly significant alteration in cases as compared to controls (Table 1).

Fig. 4 elucidates the planarity status of the 3D-QRS loop in the patients with acute myocardial infarction, which clearly exhibits a loss of planarity in these cases. The best approximate optimal surface fails to cluster most of the spatial data points.

DISCUSSION:

The existence of a *QRS plane* in the VCG of normal subjects is in itself somewhat surprising and counter-intuitive. In view of the diverse paths along which the ventricular muscle is activated, and the widely separated muscle fibers that are activated simultaneously, it would hardly be expected *a priori* that the successive vector sums of these separate events would lie in the same spatial plane.

The possibility that this apparent planarity is an artifact imposed by the conducting materials between the heart and electrodes was also excluded by Milnor [3]. Observations on the isolated rabbit heart in a homogeneous fluid medium showed that the preferred QRS plane is still present under such conditions.

Yamauchi (1979) reported that the QRS loop in anterior myocardial infarction was significantly larger with respect to width and width/length ratio than those of the normal persons. He showed that the poor planarity of the QRS loop was one of the characteristics of myocardial infarction, especially where the disease is extensive [7]. Similar observations were also made in a few other studies [8,9].

Åström *et al* [23]studied the QRS Loop Morphology and itsrelationship with the established noise level. By using a measure related to loop planarity, it was demonstrated that the alignment breakdown noise level had an essentially linear dependence on loop planarity. A planar loop corresponds to a lower breakdown noise level than does a non-planar loop. Normal subjects have VCG loops which, in general, are more planar than those of patients with myocardial infarction. They found that myocardial damage is often associated with loops which include bites, abnormal transitions or sharp edges which destroy the planarity.

The present study clearly shows that there is a complete loss of planarity of the 3D-QRS loop in AMI, with a breakdown of the alignment of the spatial planar point clusters as observed in normal controls.

It was also found that the QRS spatial loops are ordinarily closed and planar in normal controls and lose their planarity with or without being closed in the case of myocardial infarction. Planarity was lost even in a closed loop when the morphology of loop is distorted.

The planarity of the QRS loop may be lost in a number of conditions [8, 14], from which we took the most studied entity, i.e. acute myocardial infarction (AMI), for comparison with a normal loop. This study does not claim that loss of planarity is a parameter for diagnosing AMI.

In order to explain and justify the phenomenon of planarity of the 3D-QRS loop and its breakdown in AMI, we would like to put forward from the existing literaturecertain basic physiological aspects of ventricular depolarization, source description of the depolarization wave, its propagation in the heart and volume conductor and their evaluation in the field points of electrophysiological recording.

The classical theory of Electrocardiology, introduced by Einthoven [24] and co-workers assumes that the human body is a part of an infinitely extended, homogeneous conductor in which the heart's electric sources are represented by a single, time-varying current dipole -- depicted as a two-dimensional heart vector at a fixed location. As the electrodes are placed relatively remote from the cardiac source, it is postulated that the potentials at the three extremities, namely right arm, left arm and central lower torso, as generated by the heart vector are the same as those generated at the vertices of an equilateral triangle. The heart vector thus represents the vector sum of all elemental current dipoles at the centroid of the heart. Wilson *et al* introduced a more general solid-angle theory and proposed a double-layer source instead of a single, fixed-location dipole[25,26]. McFee and Johnston[27], and Schmitt[28], introduced the distributed character of cardiac depolarization sources and generalized lead vector into the lead-field concept. Body-surface potential mapping studies also disagree with a single, fixed-location dipole source[29].

Accordingly, depolarization consists of a complex of excitation waves moving through the tissue by means of active propagation. From an extracellular viewpoint, excitation waves consist of a *source-sink* pair. (Fig. 5)

The source model is based on the assumptions that the elementary dipoles line up with the direction of the wavefront propagation and have uniform strength. It is known as the uniform double layer (UDL) and is based on the solid angle theory of Wilson *et al*. [25,26]. Following a local stimulus in the myocardium, the cells in the direct vicinity of the stimulus are activated. The interiors of these cells are coupled through several low-resistive *connexins* to neighboring cells and act as functional syncitium. As a result, these cells are activated as well and in turn activate their direct neighbors. At the macroscopic level, this can be described in terms of an activation boundary which propagates like a planar wave-front through the myocardium. The UDL theory postulates a double-layer current of uniform strength at the surface separating myocytes that are depolarized and those that are still at rest, i.e. polarized: the *activation wave-front*. Following initiation, the activation wave-fronts propagate throughout the myocardium and the UDL sources form the major generator of the currents during this period, which ends when all myocytes have been activated[30].

The potential generated by the distributed *sources and sinks* of the UDL systemis proportional to the solid angle of the excitation wave from the field point (Fig. 5) and implies planar boundaries of the myocardiumat the propagating wave-front. The infinite medium potentials that are generated by the sequence of activation wave-fronts assume the electrical conductivity of the entire infinite medium to be uniform.

However, the electrical conductivity of blood is three times higher than that of the isotropic representation of myocardial tissue. The effect of this inhomogeneous conductivity on the potential field is generally known as the *Brody effect*[31]. Also,the cardiac electrical activity is observed in a three-dimensional, bounded, irregularly shaped and inhomogeneous volume conductor[32],be it the thorax or some fluid-filled container used during *in vitro* experiments, rather than an infinitely extended homogeneous volume conductor.

In the UDL model, both the strength of the double layer and the conductivity of the medium in which this equivalent source is located are assumed to be independent of the direction in which the cardiac fibers are aligned within the myocardium. In reality, the strength and direction of elementary sources depend on fiber orientation[30]. The electrical current in the passive myocardium is conducted more easily along the fiber direction than in a direction across the fibers. Thus, at a macroscopic local level, the conductivity is a tensor rather than a scalar[30]. This means that the conductivity should be specified by the components, like longitudinal conductivity or transverse conductivity. As a consequence of fiber orientation, the elementary dipole strengths of a depolarization wave-front, the conductivity of the medium, or both, may be assumed to be an anisotropic and possibly non-uniform, source model [30].

In various experimental models, the potential profiles and electrograms are based on the simple model of UDL source, isotropic electrical conductivity, and a Huygens type of propagation [30]. Huygens' wave-front model [33] is utilized to simulate the propagation of depolarization in the excitable tissue and based on the assumption of constant wave propagation velocity. From a given point of time and wave speed, it is possible to locate the wave-front at the next time point. From a point source, it is essentially like dropping a pebble into a pond and observing the path of the first wave.

Although, anisotropy is an inherent property of fiber structure and affects electrical propagation and conductivity, yet the UDL source model has been shown to be a useful concept. For the entire heart, anisotropy is not uniform, because of the complex arrangement of muscle layers of the myocardium [33]. This tends to lessen the overall effect of anisotropy, in particular when the potentials observed and recorded are those on the body surface, which are substantially remote. It is reasonable, therefore, that while describing the potential in the region outside the heart, the application of the UDL, being the simplest of all models is still highly relevant.

In addition, the Eikonal Curvature Model [34]propounds the effect of the curvature of the wave-front on the speed of propagation. The direction of current flow corresponds to the direction of the maximum rate of decrease in potential, and the magnitude of the current density will be proportional to the magnitude of this rate of change.Essentially, a concave wave-front creates a current density that is higher than that of a plane wave, because the wave is propagating into a smaller area and this causes the wave to accelerate. The opposite is true for a convex wave-front in which the wave moves into a larger area of resting tissue, which causes the wave to decelerate (Fig. 6). Accordingly, the activation wave-front of depolarization tends to assume a uniform propagation velocity and a planar orientation in a UDL system.

In this connection, we propose another deductive interpretation of the planarity issue.

The present study shows that in the normal control subjects the plane consisting of 3D-QRS loop passes through the origin (0, 0, 0), so its equation reduces to z = ax + by where a and b are real constants, i.e. z is a linear combination of x and y. But what does this imply physically? If we set y to be zero, the above equation takes the form z = ax implying, z to be directly proportional to x. Similarly, setting x at zero, we obtain z = by, implying z to be directly proportional to y. These observations collectively turn to the simple fact that x, y and z are of the same rank-status except for some constant multipliers. x alone cannot accelerate to grow as a square or cube or in higher powers keeping behind y and z as it would be in the case of $z= ax^2 + by$ or $z = ax^3 + by$ etc. A similar conclusion holds good for y and z also. In terms of signal propagation, this reduces to the fact that the electrical wave components in the heart, and in the surrounding media, propagate in three mutually orthogonal directions in some uniform fashion. Any one of them cannot propagate at a higher order of magnitude than the others because all of them are linearly related.This linearity also indicates that their rate of propagation in any of the three mutually orthogonal directions remains constant. However, this uniformity in wave propagation does not necessarily imply structural homogeneity of the heart and/or the volume conductor. It only indicates some directional symmetry with respect to a single loop in the context of depolarization wave propagation and the recording the magnitude of the extracellular potential.

Accordingly, we remain cautious using the term ‘uniformity’ and ‘homogeneity’ in order not to create any confusion. It only indicates that instead of being inhomogeneous and non-uniform as a whole, this non-uniformity has a uniform distribution in three mutually orthogonal directions. In certain pathological states like acute myocardial infarction, this uniformity in wave propagation is perturbed due to the disturbance in directional symmetry leading to the development of nonlinear relationships among the three concerned variables. Moreover, the planarity of individual loops indicates that there are several components and compartments in the functional heart-conductor system, which maintains homogeneity and uniformity in wave propagation irrespective of three mutually orthogonal directions. But at the same time, the entire heart and volume conductor system remain inhomogeneous and anisotropic.

Acute myocardial infarction results in loss of structural and functional integrity of the different layers of heart, depolarization source disruption, macroscopic conduction anomaly, development of a current of injury, altered excitability etc[35]. Alteration of the magnitude of the action potentials leads to a change of the intensity of the line density of the membrane current that affects the UDL strength. There is alteration in the effective distance and orientation of the source-sink pair to the field point of recording, and reduction in the number of cardiac fibers involved, i.e., the extent of the source region, an alteration in the solid angle of the source region, loss of Huygen's type of propagation and finally altered inhomogeneities in conductivity within the volume conductor. All these adversely affect the magnitude of the extracellular potential during depolarization, the loss of homogeneity, the increase in anisotropy, and Brody effect lead to complete loss of planarity of the 3D-QRS loop in AMI, with breakdown of the alignment of the spatial point clusters.

The present paper, in an attempt to explain the probable cause of planarity of the spatial QRS loop in normal persons and its loss in AMI, reports certain characteristic features in support of the UDL theory of the spread of depolarization.

Funding:

No external funding. Research activities were conducted utilizing routine clinical data and departmental infrastructure.

Acknowledgments:

1. The Principal,
Medical College Kolkata
88, College Street.
Calcutta – 700 073, India.

For permitting us to undertake the present research work and providing all necessary support and logistics.

2. The Head
Dept. of Cardiology
Medical College Kolkata
88, College Street.
Calcutta – 700 073, India.

For permitting us to carry out the clinical work out and collect all patients related data and information.

Conflict of interest:

Nil

Declaration:

1. There are no relationships with industry or any financial institution.
2. Authors take responsibility for all aspects of the reliability and freedom from bias of the data presented and their discussed interpretation.

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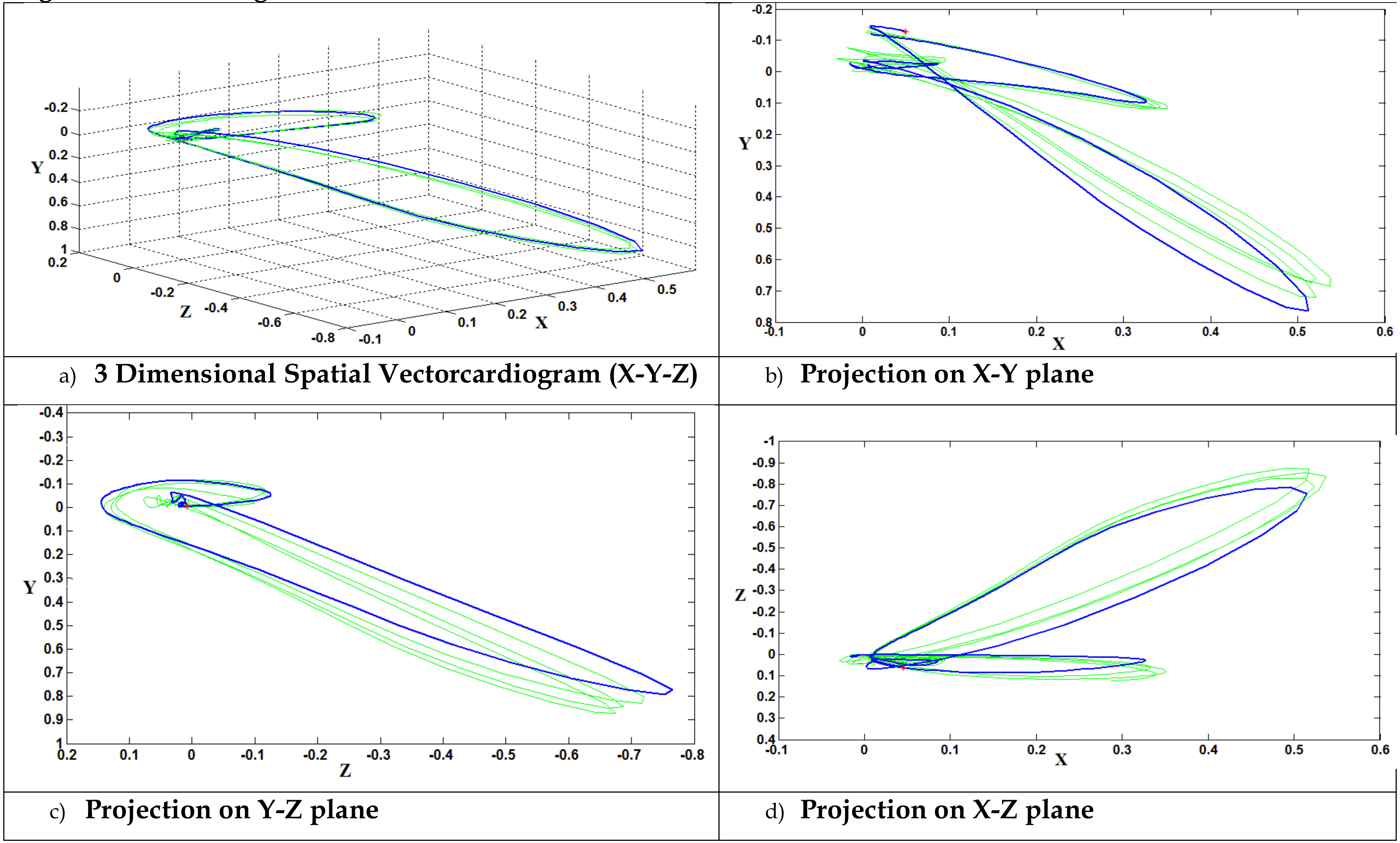
Table 1: Comparison of the Goodness of Fit criteria between Control Volunteers and Patients of AMI with respect to surface fit of the 3D-QRS loop			
	Control (n = 15)	**AMI Patients (n = 15)**	**P value (1 tailed)**
SSE	0.4043 ± 0.47658	19.222 ± 649.8735	0.0063264
RMSE	0.07132 ± 0.0015203	0.465488 ± 0.11712	0.00028
R^2	0.86528 ± 0.0214346	0.437638 ± 0.10103527	0.0000637
Adjusted R^2	0.85812 ± 0.0228172	0.4128287 ± 0.1100472	0.0000639

Fig. 1: Vectorcardiogram in normal control



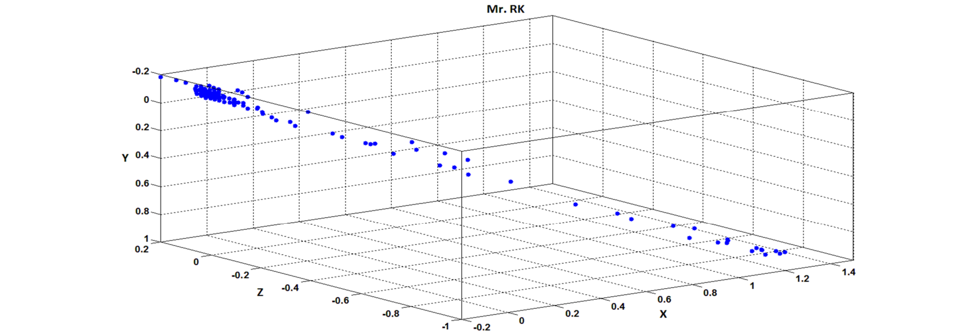
a) **3 Dimensional Spatial Vectorcardiogram (X-Y-Z)**

b) **Projection on X-Y plane**

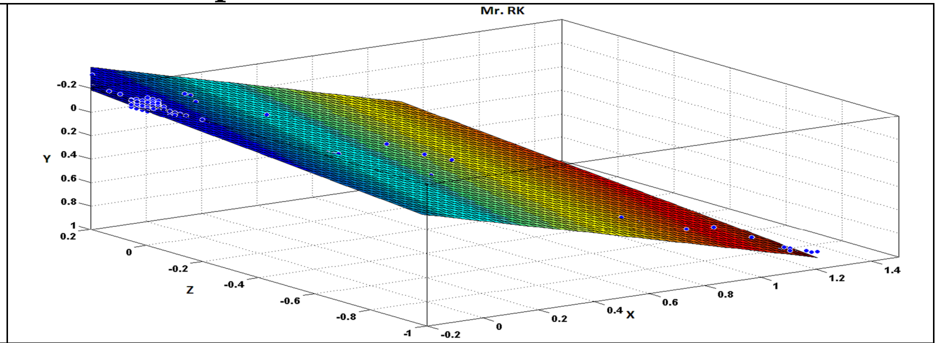
c) **Projection on Y-Z plane**

d) **Projection on X-Z plane**

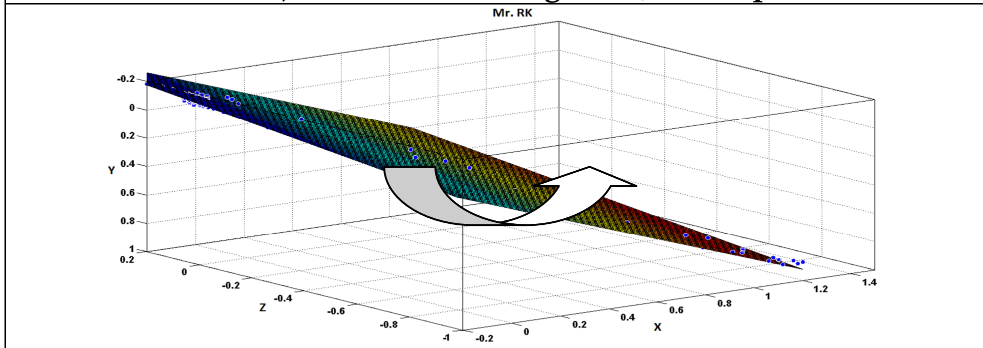
Fig. 2: Manual rotation of the plane in order to *"Fit"* the 3D-QRS Loop



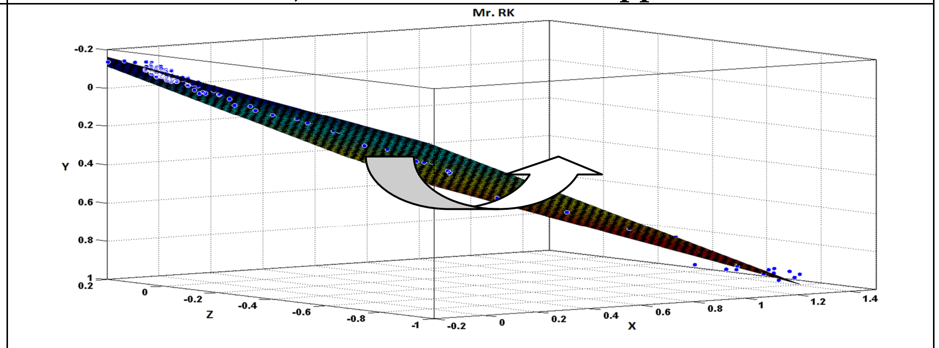
a) Scatters showing 3D QRS Loop



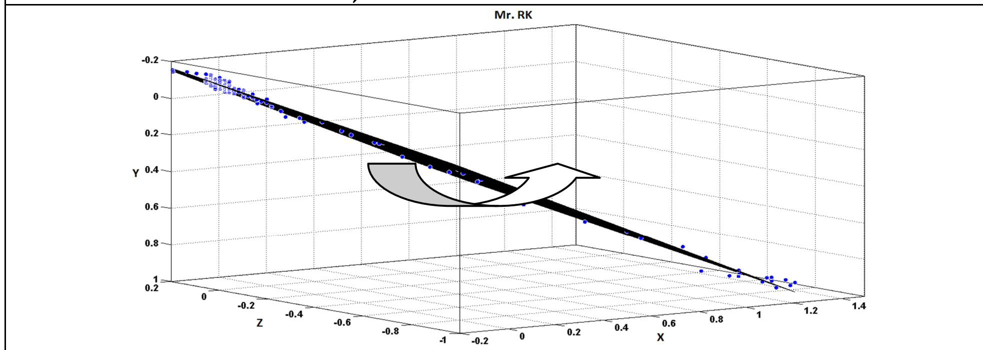
b) A Planar surface is applied



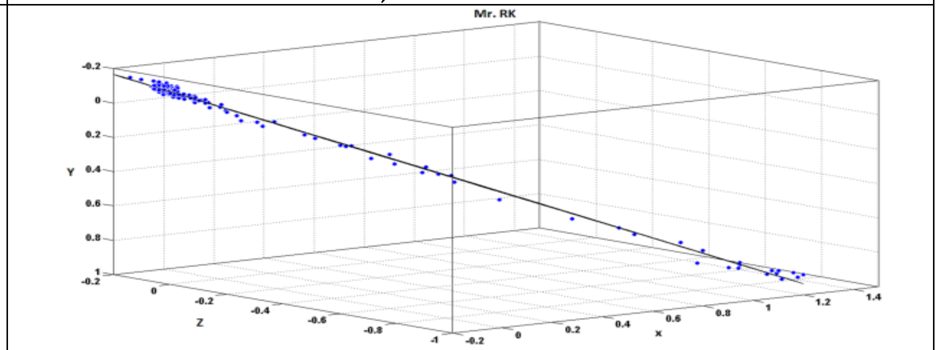
c) The surface is rotated



d) Further rotated



e) Still further rotated



f) Further rotated to fit

Fig. 3: QRS Spatial Loop in 3D Space in Normal Controls (left). The said 3D-QRS Loops are fitted in a plane (right)

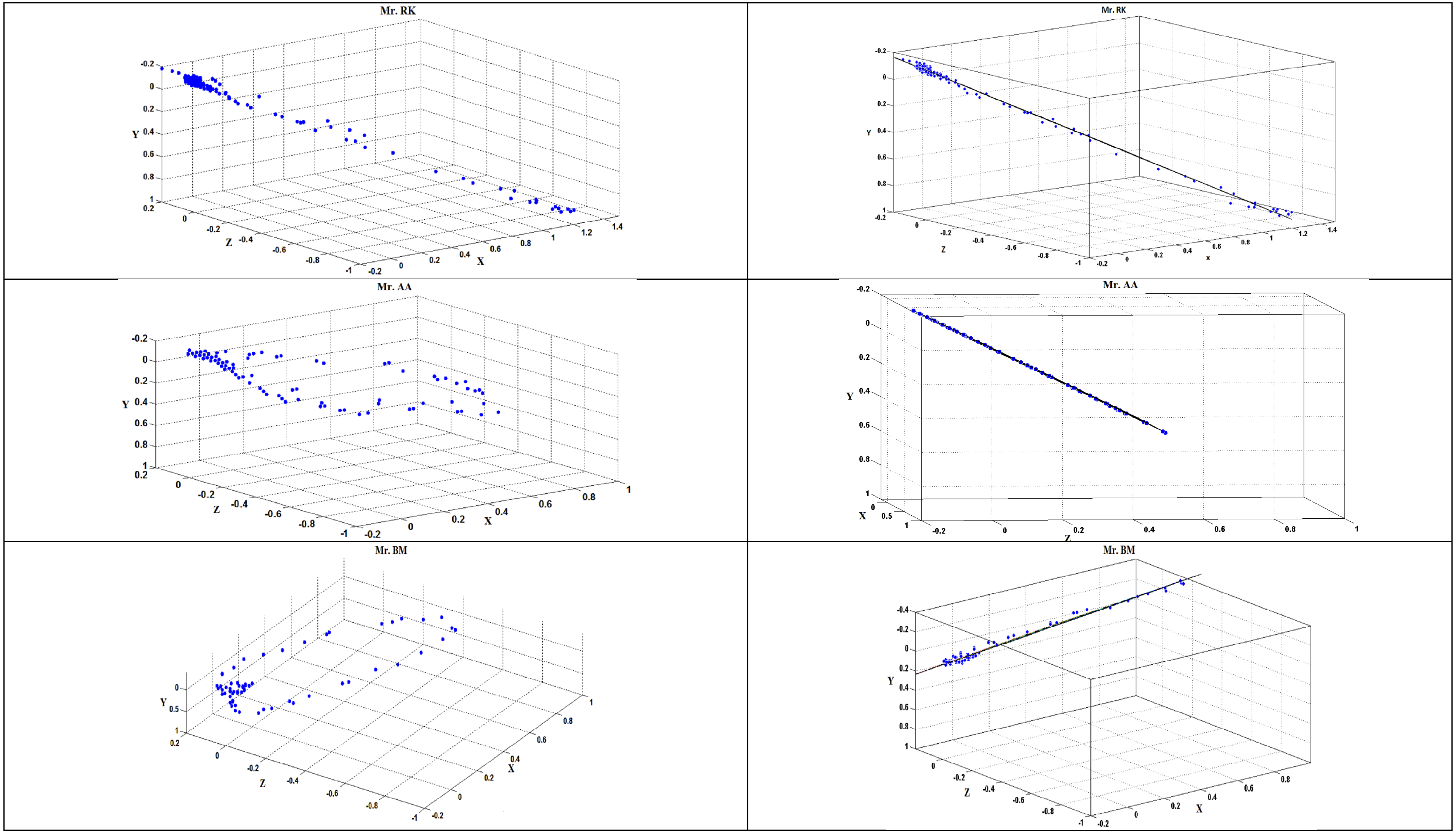


Fig. 4: **QRS Spatial Loop in 3D Space in Cases of acute myocardial infarction (left). The Loops do not fit in a plane (right)**

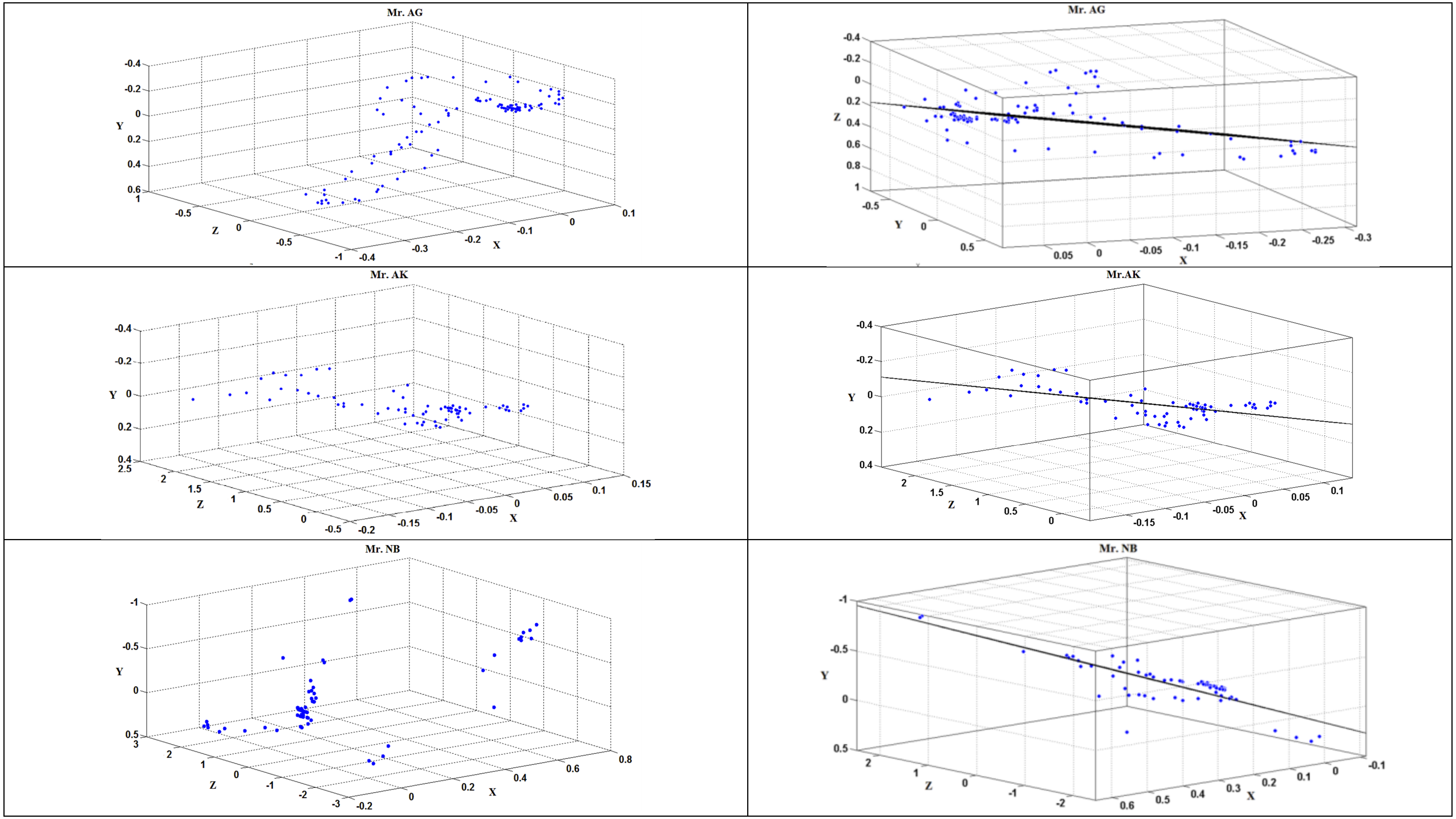


Fig. 5: **Propagating depolarization wave front**

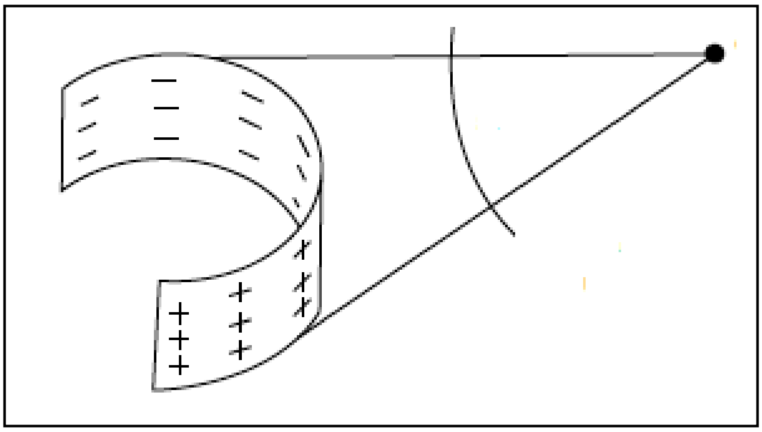


Fig. 6: **A concave wave-front creates a high local current density that causes the wave-front to accelerate and flatten out as it propagates (*left*). A convex wave-front creates a low local current density that causes the wave-front to decelerate and flatten out (*right*).**

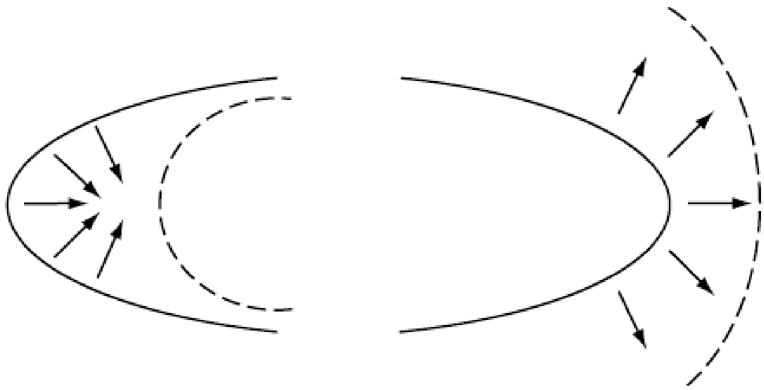


Figure legends

Fig. 1: Vectorcardiogram in normal controls

Fig. 2: Manual rotation of the plane in order to *"fit"* the 3D-QRS loop

Fig. 3: QRS Spatial Loop in 3D space in normal controls (left). The 3D-QRS loops are fitted in a plane (right)

Fig. 4: QRS spatial loop in 3D space in cases of acute myocardial infarction (left). The loops do not fit in a plane (right)

Fig. 5: Propagating depolarization wave front

Fig. 6: A concave wave-front creates a high local current density that causes the wave-front to accelerate and flatten out as it propagates (*left*). A convex wave-front creates a low local current density that causes the wave-front to decelerate and flatten out (*right*).