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Planarity of the spatial QRS loop of vectorcardiogram is a crucial diagnostic and prognostic parameter in acute myocardial infarction

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ABSTRACT

Vectorcardiogram (VCG) is a recurring, near-periodic pattern of cardiac dynamics that graphically represents the trajectory of the tip of cardiac vectors in three dimensional space with varying time. VCG is constructed by drawing the instantaneous vectors from a zero reference point according to direction, magnitude and polarity in the space. It is more informative and sensitive than conventional ECG as an evaluation tool of the physiology of cardiac dynamics.

Each heart cycle consists of three loops corresponding to P, QRS, and T wave activities in VCG. The morphological assessment of the QRS loop was carried out in order to analyze the spatial vectors of the ventricles and their patho-physiological correlation in various cardiac diseases. It was found that, the three dimensional QRS loop in healthy individuals lies in a plane. It is rather surprising that the normal spatial QRS loop lies in a single plane, considering the complex structure of the ventricular musculature together with the numerous possible pathways along which the depolarization impulse passes. The highly curious phenomenon of planarity of the spatial QRS loop was explained by uniform double layer (UDL) theory, which postulates the phenomenon of activation wave-fronts that propagate with a constant & uniform rate throughout the myocardium.

Acute myocardial infarction results in loss of structural and functional integrity of the different layers of heart, perturbation of the uniformity in wave propagation due to the disturbance in directional symmetry, development of nonlinear relationships among the concerned variables, loss of homogeneity and complete loss of planarity of the 3D-QRS loop.

The planarity of the 3D-QRS loop is a highly restricted and sensitive parameter and a characteristic feature of normal heart and can be utilized as a test for diagnostic screening of cardiac normalcy and the loss of planarity may be a conspicuous feature of AMI. It will be reasonable to study the morphology of the spatial QRS loop in patients of AMI throughout the course of disease and also in a regular interval through the long-term follow up period. It is expected that with the reperfusion, recovery and salvage of the diseased myocardium; the homogeneity and the intensity of the line density of the membrane current of the UDL would gradually recover with retrieval of the planarity of the spatial QRS loop. The temporal pattern of characteristics alteration of the QRS loop planarity with the natural course of the disease requires intensive evaluation.

We propose that, the planarity of the spatial QRS loop, its loss, involution and reversal is a temporal series of events in AMI and also a crucial diagnostic and prognostic parameter.

Introduction

Heart is an electrically active organ which initiates a wave of electrical depolarization that propagates through the cardiac muscle causing mechanical contraction. They are represented by time-varying current dipole and termed as vectors. Movement of the electrically charged particles that occur during spread of the cardiac action potential generates such vectors. Vectorcardiogram (VCG) represents a graphical representation of the trajectory of the tip of these vectors in three dimensional space with varying time [1].

The VCG loops contain three-dimensional recurring, near-periodic patterns of cardiac dynamics. Each heart cycle consists of three loops corresponding to P, QRS, and T wave activities. The VCG signals are projected onto different planes (X-Y plane, X-Z plane and Y-Z plane) to capture the time-space correlations in the two dimensions keeping the other variable constant, or plotted as a static attractor in a 3D space that

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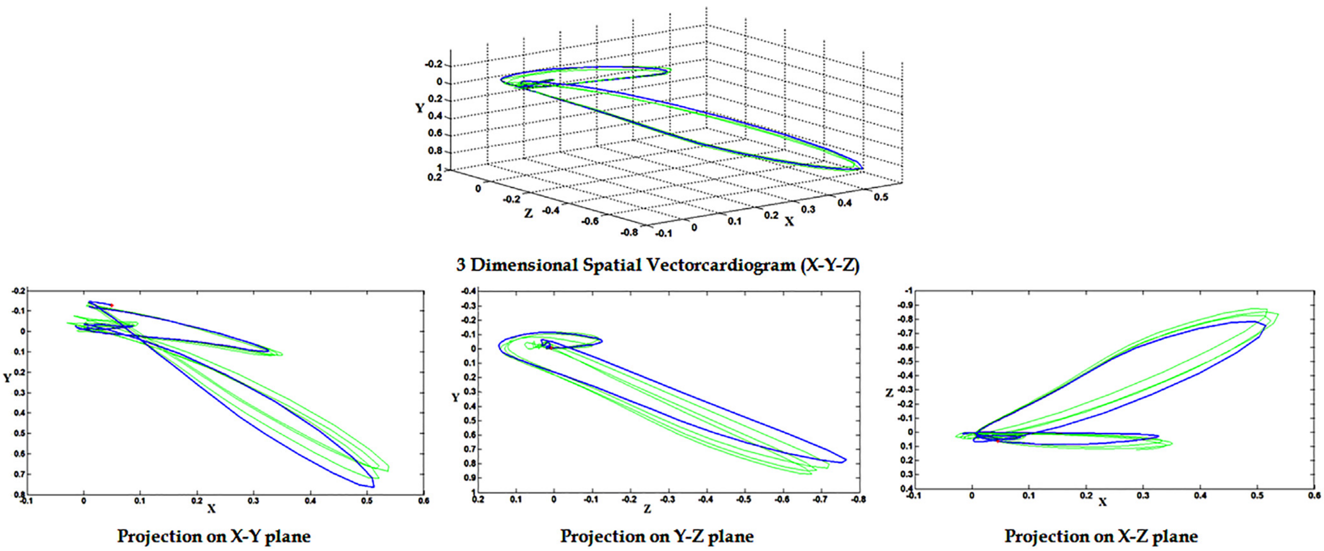

Fig. 1. Vectorcardiogram in normal control.

provides the topological relationships when all the variables are changing (Fig. 1).

VCG is constructed by drawing the instantaneous vectors from a zero reference point according to direction, magnitude and polarity in the space. It is more informative and more sensitive than conventional ECG because of its one extra degree of freedom as an evaluation tool of the physiology of cardiac dynamics. As a result, with the help of VCG it is possible to correlate even a minute electrophysiological alteration with the patho-physiological changes in diseases which is essential for early diagnosis [2].

The routine clinical ECG is scalar in nature. It does not represent the instantaneous vectors generated at the heart and only shows the magnitude of the component of the main electrical vector along a particular lead axis. The magnitude, direction and the polarity of the instantaneous vectors cannot be known from the ECG. Thus any small changes, early initial change or electrically compensated change of vector of heart cannot be identified from the ECG.

However, the difficulty, inaccuracy & cumbersomeness in constructing a VCG loop and lack of standardization of accepted methodology so far prevented the study of VCG to become popular.

In the recent years, the analysis of the vectorcardiogram has developed with vigour because of growing recognition that spatial analysis of the cardiac electric phenomena is likely to yield information not furnished by the conventionally recorded electrocardiogram [3,4]. Moreover, recent development and wide availability of signal acquisition system, computer based technology, mathematical and computational tools etc made VCG construction potentially easier, objectively designable and get standardized. There are a number of methodologies to construct VCG, where special lead systems are required. In a recent paper [5], Ray *et al* proposed a quasi-orthogonal lead system with I, aVF and V2 and utilized them to emulate the traditionally used Frank's orthogonal leads (X, Y, and Z respectively) [6]. They also validated these leads of conventional ECG as reasonably accurate representatives of X, Y and Z axes.

It is prudent to undertake the morphological assessment of the spatial QRS loop of VCG with respect to shape, contour, angularity and other spatial dimension in health and in disease states in order to objectively enumerate the normal features of the spatial vectors of the ventricles and also to understand their patho-physiological correlation in the state of various cardiac diseases.

Among various features and observations we would like to emphasize an interesting feature, namely the planarity of the three dimensional 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".

Review of literature

Planarity of normal QRS VCG spatial loop

There are a number of reports in the literature 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 [7]. Rochet and Vastesaeger [8] confirmed and extended this observation, reporting the variations in normality. Milnor [9] introduced quantitative expression to the QRS plane by means of the panoramic vectorcardiogram. Frank [6] 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 [6]. Seiden [10] also confirmed Milnor's and Frank's observations of the planarity of loops, and Howitt and Lawrie [11] called for an explanation of this phenomenon in terms of the spread of depolarization in the heart. Rochet and Vastesaeger [8] 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 [9], 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 and amazing 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 [12]; 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 [13]. The planarity of the QRS loop was also assessed from the degree of deviation of frontal QRS loop after lead axis rotation [14]. Mossard [15] 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 normalized with respect to the size of the loop [15].

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. In a comprehensive review on VCG by Man et al. (2015) this crucial issue has not been emphasized [3]. This is partly because the multiplicity of methodologies of constructing a 3D-VCG loop and evaluating the planarity status is 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 is not constrained by computational resources anymore, and that has generated a renewed interest in the VCG [4]. However, a proper explanation of this very interesting observation will probably not be possible until we gain more basic and fundamental physiological 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 [16]. In 2016, Sedaghat et al. [4] calculated the planarity index using the concept "geometrical area vector (GAV)", proposed by Pierre Amaud in 1989 [17]. 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 QRS loop.

In the year 2017, Ray at al [5] constructed spatial QRS loop of the VCG using I, aVF and V2 leads. 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 by computer programming, and various morphological features of this loop and its 2D planar projections were assessed (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 plane incorporating the QRS loop was determined by fitting a plane surface $z = ax + by + c$ to the three-dimensional points constituting the QRS loop and the 'fitness' was validated quantitatively using 'Goodness of fit' criteria. This plane represents a statistical model derived by least-squares fitting, where the model coefficients can be easily estimated with little uncertainty and are easy to interpret. The specific statistical measures that were studied were 'Sum of Squares Due to Error' (SSE), 'Root Mean Square Error' (RMSE), 'R^2' and 'Adjusted R^2'. A value of SSE and RMSE closer to 0 and a value of R^2 and Adjusted R^2 closer to 1 indicate a better fit and hence more accurate prediction. Accordingly, the quantitative value of these parameters provides objective and numerical characteristics of the degree of planarity of QRS loop. The study quantitatively verified and validated the earlier finding that, spatial QRS loop resides in a plane for normal controls and this planar structure is lost in acute myocardial infarction.

The highly curious phenomenon of planarity of the spatial QRS loop was explained by uniform double layer (UDL) theory [5], which postulates the phenomenon *activation wave-front*, i.e. 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 myocyte. 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.

In normal subjects the three dimensional QRS loop of VCG passes through the origin (0, 0, 0), so the equation of the overlying plane reduces to $z = ax + by$ where a and b are real constants. Thus z is a linear combination of x and y. 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. Thus 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 indicates that their rate of propagation in any of the three mutually orthogonal directions remain nearly constant and uniform [5].

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 [18]. There is 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. Thus the uniformity in wave propagation is perturbed due to the disturbance in directional symmetry leading to the development of non-linear relationships among the three concerned variables. All these adversely affect the magnitude of the extracellular potential during depolarization, the loss of homogeneity and complete loss of planarity of the three dimensional QRS loop in AMI, with breakdown of the alignment of the spatial point clusters.

Hypothesis and discussion

Thus we can reasonably assume that, planarity of the spatial QRS loop may be a characteristic feature of normal heart and can be utilized as a test for diagnostic screening of cardiac normalcy. However, detail population based study with appropriate randomization and development of a user friendly software interface are needed.

The loss of planarity of the spatial QRS loop may be a conspicuous feature of AMI. It will be reasonable to record and study the morphology of the spatial QRS loop in patients of AMI throughout the course of the disease and also in a regular pre-decided interval through the long term follow up period. It may be a rational expectation that with the reperfusion, recovery and salvage of the diseased myocardium; the homogeneity and the intensity of the line density of the membrane current of the UDL would gradually recover with retrieval of the planarity of the spatial QRS loop.

We intend to assess the evolution, loss and involution of the planarity status of the spatial QRS loop in patients with acute myocardial infarction. The phenomenon of planarity of a three dimensional spatial structure is as such a highly restricted and sensitive parameter. The loss of such planarity as explained in the earlier paragraph is in consonance with the pathophysiology of AMI. However, the status of the morphology of the QRS loop with the natural course of the disease process is not much elucidated. The temporal pattern of characteristics alteration of the QRS loop planarity will be our area of interest.

We propose that, the planarity of the spatial QRS loop, its evolution, loss, involution and reversal is a temporal series of events in case of acute myocardial infarction, which undergoes recovery without complication. It would be highly interesting to see the progressive change of the loss of the planarity status of spatial QRS loop in case of acute myocardial infarction with bad prognostic outcome and complication.

Planarity evaluation of the spatial QRS loop with its objective characterization by the 'Goodness of Fit' statistical criteria may also be an important tool of coronary circulation research.

We hypothesize that, Planarity of the spatial QRS loop of Vectorcardiogram is a crucial diagnostic and prognostic parameter in Acute Myocardial Infarction.

The current endeavor aims to substantiate the evaluation armamentarium of cardiovascular diseases (CVD) which is looming large as the new epidemic afflicting Indians at a relatively younger age with severe and diffuse form of lesions. CVD take the lives of 17.9 million people every year which is 31% of all global deaths, and are the leading cause of mortality (25%) in India, out of which ischemic heart disease and stroke are responsible for more than 80% of CVD deaths. CVD has emerged as the leading cause of death in all parts of India, including poorer states and rural areas [19].

In order to combat this growing health predicament, there is a global commitment to reduce premature CVDs to 25% by 2025 [20].

Although CAD is a fatal disease with no known cure, it is also highly predictable, preventable, and treatable even with the existing knowledge. However, the existing tests for evaluation of cardiac function are either less sensitive and less specific like scalar ECG, or grossly invasive and expensive to be affordable by the common peoples of India like Coronary angiography.

Planarity evaluation of the spatial QRS lop of VCG may be a simple, affordable and crucial supplement to the future CVD work out.

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Declaration of Competing Interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mehy.2019.109251.

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