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Quantitative Assessment of Vectorcardiographic Loop Morphology

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Abstract

Vectorcardiography (VCG), developed 100 years ago, characterizes clinically important electrophysiological properties of the heart. In this study, VCG QRS loop roundness, planarity, thickness, rotational angle, and dihedral angle were measured in 81 healthy control subjects (39.0±14.2y; 51.8% male; 94% white), and 8 patients with infarct-cardiomyopathy and sustained monomorphic ventricular tachycardia (VT) (68.0±7.8y, 37.5% male). The angle between two consecutive QRS vectors was defined as the rotational angle, while dihedral angle quantified planar alteration over the QRS loop. In VT subjects, planarity index decreased (0.63±0.22 vs. 0.88±0.10; P=0.014), and dihedral angle was significantly more variable (variance of dihedral angle, median (IQR): 897(575–1450) vs. 542(343–773); P=0.029; rMSSD: 47.7±12.7 vs. 35.1±13.1; P=0.027). Abnormal electrophysiological substrate in VT patients is characterized by the appearance of QRS loop folding, likely due to local conduction block. The presence of fragmented QRS complexes on the 12-lead ECG had low sensitivity (31%) for detecting QRS loop folding on the VCG.

Graphical abstract

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Keywords

Vectorcardiography; Planarity; Ventricular tachycardia

Introduction

The vectorcardiogram (VCG) represents heart vector movement in three orthogonal dimensions. The first VCG was constructed in 1920 by Mann [1], who called it a monocardigram. In 1938, Wilson suggested the term VCG [2] to emphasize that it reflects both magnitude and direction (vector properties) of the electromotive force produced by the heart. Wilson contrasted the VCG to the standard electrocardiogram (ECG) which is a scalar function of the heart's electromotive force over time.

Since the origin of the VCG, numerous parameters representing VCG loop morphology have been developed. VCG loop morphology can be characterized by the direction and amplitude of the instantaneous initial spatial [3] and maximum "peak" and "mean" vectors of the loop [4]. The "roundness" or principal shape of the loop has been described as the ratio of VCG loop height and width [5], or as the ratio of the second and first principal components of the orthogonal eigenvectors [6]. It has been shown that normal hearts have QRS loops which stay primarily in a single "main," or "preferential" plane [7; 8]. Therefore, several planarity

measures (planarity index [9], thickness of the loop [10], roundness of the plane [5; 11]) have been developed to characterize VCG loop morphology and to quantify how well the VCG loop fits the main plane. However, these previously developed VCG morphology descriptors are insufficient to fully characterize complex three-dimensional VCG loop morphology. We recently demonstrated that analysis of VCG QRS loops can help define abnormal electrophysiological substrate in patients with life-threatening ventricular arrhythmias [12]. The goal of this work was to further continue development of VCG loop morphology descriptors.

Methods

Study Population and VCG data

As previously described by our group [12], we retrospectively analyzed reconstructed VCG's of healthy individuals in the Intercity Digital Electrocardiogram Alliance (IDEAL) study [13], and patients with infarct-cardiomyopathy and sustained ventricular tachycardia (VT) presenting for VT ablation at Beth Israel Deaconess Medical Center in Boston, Massachusetts. We developed customized MATLAB (MathWorks, Inc, Natick, MA) software for automated ECG and VCG analysis. A median beat was constructed out of five consecutive sinus beats. The origin of each QRS VCG loop was detected as previously described by Sur et al [4]. Respiration was removed through shifting, rotating and rescaling of VCG loops, as previously described [14]. The following morphological descriptors of VCG QRS loop were measured.

Planarity Index

The planarity index (PI) was calculated using the “geometrical area vector”, $\overrightarrow{GAV}$, method [9]. $\overrightarrow{GAV}$ 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 was defined as the ratio of the magnitude of $\overrightarrow{GAV}$ to the area of the entire QRS loop (QRSA)[9].

$$PI = \frac{\|\overrightarrow{GAV}\|}{QRSA} \quad (1)$$

The plane of best fit for the QRS loop was found through a linear regression modelling approach (Figure 1A) in the form of:

$$aX + bY + cZ + d = 0 \quad (2)$$

where (a, b, c) is the normal vector to the plane in the Cartesian system. The azimuth and elevation of the normal vector were computed by converting Cartesian coordinates into polar coordinates. Absolute value of the azimuth was calculated.

$$azimuth = \tan^{-1}\left(\frac{b}{a}\right) \quad (3)$$

$$elevation = \tan^{-1} \left(\frac{c}{\sqrt{a^2 + b^2}} \right) \quad (4)$$

The positive (negative) azimuth angle was defined as the angle between the vector's orthogonal projection onto the xz-plane and the positive x-axis towards the negative (positive) z-axis in the range of 0 to +180° (-180°). The elevation of the normal vector of the main plane was defined as the angle between the vector and the positive y-axis in the range of 0 to 180°.

Roundness Index

The roundness index (RI) was measured as the ratio of the area of the QRS loop (QRSA) to the square of the maximum QRS vector ($QRS_{\max}$) passing through the origin of QRS loop [11].

$$RI = \frac{QRSA}{(\overrightarrow{QRS_{\max}})^2} \quad (5)$$

The area of the QRS loop was calculated by summing the area of the triangles formed by consecutive QRS vectors (Figure 1B).

Thickness

The thickness of the QRS loop was measured by calculating the distance between two parallel planes encompassing the horizontal QRS loop. These planes were oriented parallel to the best fitted plane of the loop, containing the furthest QRS sample points from each side of the fitted plane (Figure 1C).

Definition of a smallest unit plane

Vectors obtained by joining the QRS loop origin to each sample on the QRS loop were defined as QRS loop vectors. Two consecutive loop vectors were then used to define a unit plane (P_n) (Figure 1D) as follows:

$$V_n = VCG_n - Origin, \quad (6.1)$$

$$V_{n+1} = VCG_{n+1} - Origin \quad (6.2)$$

$$P_n = \vec{V}_n \times \vec{V}_{n+1} \quad (6.3)$$

Dihedral Angle

Two consecutive unit planes were compared. The dihedral angle (torsion angle, θ_k) between them (Figure 1D) was calculated as follows:

$$\theta_k = \cos^{-1} \left(\frac{P_n \cdot P_{n+1}}{\|P_n\| \|P_{n+1}\|} \right) \quad k=1, 2, 3 \dots n-1 \quad (7)$$

Plotted dihedral angles over a single QRS loop illustrate changes in the VCG QRS's main plain changes over time. The mean dihedral angle was calculated for the entire QRS loop to assess the overall mean planar alteration over time.

Rotational Angle

Rotational angle was defined as the angle between two consecutive QRS loop vectors (Figure 1D). As described above (in subsection E), QRS vectors were defined as vectors from the origin of the QRS loop to each sample point along the QRS loop.

Variability of the dihedral and rotational angles across QRS

Variability of the dihedral angle and rotational angle across the entire QRS loop was measured by variance and Root Mean Square of the Successive Differences (rMSSD).

Autocorrelation analysis of rotational and dihedral angles

Autocorrelation measures the correlation of a time series and the same series lagged by one or more time units. The lag-1 autocorrelation coefficient, r_1 , was defined with a lag of one and demonstrates the correlation of the first N-1 observations of a time series, x_t , $t = 1, 2 \dots N-1$ and the next N-1 observations of x_t , $t = 2, 3 \dots N$. The correlation between x_t and x_{t+1} is defined as follows:

$$r_1 = \frac{\sum_{t=1}^{N-1} (x_t - \bar{x}_1)(x_{t+1} - \bar{x}_2)}{\left[\sum_{t=1}^{N-1} (x_t - \bar{x}_1)^2 \right]^{1/2} \left[\sum_{t=2}^N (x_t - \bar{x}_2)^2 \right]^{1/2}} \quad (8)$$

where $\bar{x}_1$ is the mean of the first N-1 observations and $\bar{x}_2$ is the mean of the last N-1 observations.

Lag-1 autocorrelation coefficients (ACC) were calculated to determine non-randomness in changes of rotational and dihedral angles over the QRS loop, as well as to identify an appropriate time series model if the data set was not random. We previously demonstrated meaningful changes in the speed of the heart vector over 1/10th of the QRS loop [12]. Thus, in this work we measured lag-1/10th of QRS duration ACC.

QRS loop morphology and changes of the Dihedral and Rotational angles over QRS loop

In order to characterize QRS loop morphology and the patterns of temporal changes in rotational and dihedral angles, we plotted rotational and dihedral angles over QRS loop time, and qualitatively described observed differences in QRS loop morphology and the pattern of temporal changes in rotational and dihedral angles.

Quantitative assessment of QRS loop folding and its correlation with fragmented QRS complexes

Spatial QRS vectors were projected on the main plain of the QRS loop. The signed angle between each projected QRS vector and the projection of the maximum QRS vector was measured (θ_{proj}). Folding was defined as the change of the sign of the slope of θ_{proj} plot over time. Timing of each “folding event” was marked on a median QRS loop for all patients with VT. To determine whether and how QRS loop folding was manifest on 12-lead ECGs, each “folding event” was tracked on each ECG lead. Coexistence or discrepancy in time of the appearance of QRS loop folding on the VCG and a QRS notching/fragmentation [15] was evaluated. A fragmented QRS complex was considered present [15] if a notch in 2 contiguous anterior (V1–V5), inferior (II, III, aVF), or lateral (I, aVL, V6) leads was observed by two independent observers (GS and LGT).

Statistical Analysis

Statistical analyses were conducted using Stata 14 (StataCorp, College Station, TX). Measured VCG loop parameters were compared between two groups of subjects (healthy controls vs. patients with infarct-cardiomyopathy and VT). Normally distributed continuous variables were presented as mean $\pm$ standard deviation (SD) and were compared using a standard t-test. Pearson's chi-squared test was used to compare categorical variables. The nonparametric Wilcoxon rank-sum was performed to compare continuous variables with skewed distribution. Median and interquartile range (IQR) were reported to characterize non-normally distributed parameters.

Circular statistics were used to compare circular variables (with scales between 0 and 360 degrees) between groups using Watson U-square and Kuiper statistics. The mean direction of each circular vector variable was determined. The mean vector strength was calculated as the length of resultant divided by the number of observations. Circular range was reported as the length of smallest arc including all observations.

Sensitivity and specificity of the fragmented QRS on 12-lead ECG and QRS loop folding on VCG, relative to each other, were calculated in a two by two table.

Results

Demographic and Clinical Characteristics of Cases and Controls

As previously described [12; 16], participants of the IDEAL registry, who served as controls in our case-control study, were free of significant cardiovascular disease at the time of enrollment. All IDEAL participants were free of documented chronic illnesses and had a normal physical examination, a normal 12-lead ECG in sinus rhythm, a normal echocardiogram, and normal ECG exercise testing, all of which were performed to rule out subclinical cardiovascular disease. As expected, healthy controls were significantly younger than patients with infarct-cardiomyopathy and sustained ventricular tachycardia (Table 1) with similar gender distributions.

Post-MI scar was localized to the antero-septal left ventricular (LV) wall in 3 patients, inferior LV wall in 1 patient, and lateral LV wall in 4 patients. All study participants included in the “VT Cases” group subsequently (after recording of index ECG in sinus rhythm) underwent successful ablation of sustained monomorphic ventricular tachycardia. In all 8 post-MI VT cases monomorphic VT was induced during VT ablation, which verified the presence of an arrhythmogenic substrate at the time 12-lead ECGs were recorded for VCG analysis.

Roundness, thickness, and planarity of QRS loops

A comparison of patients with VT and healthy controls is shown in Table I. There was no significant difference in QRS loop roundness between the two groups. Importantly, PI was significantly larger in healthy controls than in VT cases, demonstrating that the QRS loop of healthy individuals can fit within one main plane better than in patients with VT.

Circular statistic: comparison of the main loop normal vector

Circular statistic results are reported in Table 2. The distributions of all but one circular variable were unimodal (Rayleigh and Kuiper tests $P < 0.0001$). Azimuth distribution of the normal vector to the QRS plane was uniform (Rayleigh test $P = 0.122$; Kuiper tests $P = 0.156$), which highlights the variability of patient-specific electrophysiological substrate in different post-MI patients (Figure 2). Azimuth of the normal vector to the QRS plane was significantly different in VT cases compared to healthy controls. There was a trend towards smaller elevation of the main loop normal vector in VT cases which demonstrated that position of the main QRS loop plane tended to be more horizontal in VT cases than in healthy control. Elevation and azimuth of the spatial QRS vector were significantly different between both groups as well: in VT cases the spatial QRS vector pointed backward and slightly rightward, whereas in healthy controls the spatial QRS vector pointed forward and leftward.

Rotational Angle of the QRS Loop

Mean rotational angle was smaller in VT cases than in healthy controls (Table 2), reflecting slower ventricular conduction. Variability of the rotational angle across the QRS loop was similar in VT cases and healthy Controls (Table 1).

Dihedral Angle of QRS Loop

Mean dihedral angle was larger in VT cases than in healthy controls (Table 2). In VT cases there was significantly more variability in the dihedral angle as measured by increased variance and rMSSD of the dihedral angle across the QRS loop (Table 1).

Plot of the rotational and dihedral angles over QRS loop time

Dynamic changes in rotational angle were compared between VT cases and healthy controls in Figure 3. As demonstrated, rotational angles changed abruptly in VT cases which caused multiple phases and nonlinearity in cumulative rotation. In comparison, the rotational angle of healthy controls varied smoothly over the entire QRS duration.

Healthy individuals had gradual, smooth, and very small plane changes throughout the QRS loop (Figure 3A), and the overall QRS loop demonstrated high planarity (on average, about 90% of all points on the QRS loop fit in one single plane). Among patients with VT, dihedral angle changes were abrupt and indicated less planarity (Figure 3B).

Autocorrelation analysis of rotational and dihedral angle

Lag-1 ACC for both rotational and dihedral angles were virtually identical in healthy controls (Figure 4A) and patients with VT (Figure 4B). Thus, non-randomness of dynamic changes in rotational and dihedral angles across the QRS loop was established.

Differences between study groups at lag-1/10th of QRS duration were borderline for rotational angle, and statistically significant for the dihedral angle. In VT cases (Figure 4B), ACC at lag-1/10th of QRS duration for dihedral angle was significantly larger (and always positive, 95% CI 0.016 to 0.218) compared to healthy controls (Figure 4A) which were characterized by negative ACC values (95% CI -0.107 to -0.059).

Qualitative features of QRS loop morphology

The main qualitative feature of abnormal QRS loops in patients with MI and VT substrate was the presence of “folding” (Figure 5). Folding of the QRS loop was observed exclusively in VT cases. The degree, location, and shape of QRS loop folding was variables in all VT cases. Visual observation revealed an association between QRS loop folding and notches on the ECG QRS complex.

Comparison of QRS loop folding on VCG and fragmented QRS complexes on 12 lead ECG

A two by two table comparing VCG loop folding and 12-lead ECG QRS complex fragmentation is presented in Table 3. In the 8 VT cases, 26 total folding events were detected on QRS loops (mean 3.25 folding events per patient). Only 8 out of 26 total QRS loop folding events corresponded to the presence of QRS notching on the 12-lead ECG [15]. Therefore, although no false-positive folding events were found, the sensitivity of QRS fragmentation for detecting QRS loop folding was low (31%). If the presence of any QRS complex notching was included (including notches that did not meet the previously defined definition), sensitivity increased to 58% at the expense of an increase in false-positive folding events (n=4). In these 4 false positives, QRS notching was found only on a single ECG lead. There were 11 instances where QRS loop folding did not correspond to any notching on the surface ECG (false negative rate 42%).

Discussion

In this study we described characteristic features of QRS loop morphology in patients with post-infarct scar and a documented substrate for life-threatening ventricular arrhythmias. These features included QRS loop folding, presumably due to areas of scar/conduction block. In these cases, the QRS vector is forced to repeat nearly the same path at a different point in time during ventricular activation. We demonstrated that fragmented QRS complexes on the 12 lead ECG had low sensitivity for detection of QRS loop folding. We replicated classical VCG loop morphology descriptors (planarity, roundness, thickness) and

developed novel quantitative metrics (rotational and dihedral angles). We identified QRS loop morphology characteristics (QRS loop planarity index, variance and rMSSD of dihedral angle, and autocorrelation of dihedral angle at lag-1/10th of QRS duration), which deserve further evaluation as potential VCG risk markers of sudden cardiac death.

Classical and novel descriptors of VCG loop morphology

Wilson and Johnston [2] qualitatively described QRS loop morphology and noticed that “notching of the QRS complex depends upon irregularities in the growth and decline and in the changes in direction of the cardiac electromotive force”. It is well established that the direction of the heart vector at a given instant during the QRS loop corresponds to the direction in which the excitatory process is spreading through the ventricular muscle. Therefore, detection of irregularities in ventricular conduction is extremely important. However, visual observation of the VCG QRS loop is often subjective and is susceptible to intra- and inter-observer variability. In this work we attempted to improve VCG analysis using quantitative parameters describing QRS loop morphology. Drawing unit plane vectors from the QRS origin to each sample on the QRS loop revealed a phenomenon of QRS loop “folding”. Folding of the QRS loop represents rapid and sudden changes in the direction of ventricular activation and appears to be a typical manifestation in patients with post-MI scar and sustained monomorphic VT. In only 31% of cases QRS loop folding correlated with fragmented QRS complexes on the 12-lead ECG; therefore, three dimensional analysis revealed potentially important information which could be hidden on a standard 12-lead ECG. Further studies are needed to investigate if folding is present in all (including arrhythmia-free) patients with post-MI scar (serving as a VCG manifestation of the Selvester score [17]), and in patients with non-ischemic structural heart disease.

The control group in our study was obtained from participants in the IDEAL study [13] which was a cross-sectional analysis of apparently healthy individuals. While manifest cardiovascular abnormalities were clearly absent in IDEAL study participants, it is also possible that some participants had subclinical cardiovascular disease. Significantly larger QRS loop thickness and similar roundness of the QRS loop in healthy control subjects and VT patients suggested that subclinical heart disease might be present in some control patients. Unfortunately, absence of follow-up did not allow us to verify this hypothesis.

QRS loop thickness in both groups of study participants was similar to values previously reported by Ohshita [10]. QRS loop planarity was similar to values previously reported by Arnaud et al [9], and QRS loop roundness in our study was similar to results previously reported by Horinaka et al [11]. Thus, we successfully replicated classical descriptors of VCG loop morphology. These three parameters (roundness, thickness, and planarity) reliably describe basic QRS loop morphology features, and should be routinely reported in each VCG study. Out of three classical VCG loop descriptors, however, planarity seems to carry the best discriminative accuracy in terms of identifying structural heart disease. At the same time, in post-MI VT cases, the QRS loop progresses through multiple planes because of QRS loop folding, which prompted us to develop rotational and dihedral angles as additional novel descriptors of QRS loop morphology.

Measurement of variability in the dihedral angle over the QRS loop captured important differences between VT cases and healthy controls and enabled quantification of inhomogeneity of ventricular conduction which is a well-known risk factor for arrhythmogenesis.

In this study we calculated the autocorrelation of the dihedral angle time series at lag-1/10th of QRS duration to characterize heterogeneity of ventricular activation. We observed that VT cases were characterized by positively autocorrelated series, whereas healthy subjects were characterized by negatively autocorrelated series. Positively autocorrelated series characterized persistent changes in dihedral angles which meant an increase in one time series of dihedral angle followed by a proportionate increase in the next time series of dihedral angle. Positively autocorrelated series at lag-1/10th of QRS duration were consistent with our observation of folding QRS loops in VT cases. Folding of the QRS loop is characterized by steadily increasing dihedral angles, up to the point of the maximum dihedral angle, which then decrease gradually. Folding takes longer than 1/10th of QRS duration as a shift in time by 1/10th of QRS duration produced positive autocorrelation. Thus, folding (i.e. increasing dihedral angle), which started at any one 1/10th of QRS duration, continued and even increased during the subsequent 1/10th of the QRS duration. After dihedral angle reached its maximum it started decreasing for at least 2/10ths of QRS duration: the initial decrease of dihedral angle at any given 1/10th of QRS is followed by an even steeper decrease of dihedral angle at the subsequent 1/10th of the QRS duration.

All together this produced positive autocorrelation at lag-1/10th of QRS duration. On the other hand, negatively autocorrelated series demonstrated that an increase of dihedral angle in any given 1/10th of QRS duration resulted in a proportionate decrease of dihedral angle in the next 1/10th of QRS duration. Therefore, the resultant QRS loop remained essentially flat. This observation was consistent with the high planarity of QRS loops in healthy controls.

Further studies of autocorrelation at lag-1/10th of QRS duration for dihedral angle, variance and rMSSD of dihedral angle are needed to determine their clinical and prognostic significance for risk stratification of sudden cardiac death.

Position of the QRS loop main plane

Our study revealed significant differences in the orientation of the main QRS plane in healthy controls compared to post-MI patients with VT. In healthy controls, normal vector to the main QRS plane had an azimuth near $\pm 70^\circ$ and elevation near 45° . Thus, the main QRS loop had a prominent projection in the frontal plane. However, in post-MI patients with VT, the normal vector of the main QRS plane had about twice smaller azimuth (about $\pm 35^\circ$) and elevation (about 30°). Thus, the best plane to project the main QRS plane in VT patients was horizontal (or transverse) and not frontal.

These differences potentially have significant clinical importance. The traditional 12-lead ECG is good at representing heart vector movement in the frontal plane, and the 12-lead ECG is therefore good at representing the entire QRS loop morphology in healthy subjects. A predominantly horizontal main QRS plane (a characteristic feature of post-MI VT cases),

however, has poorer representation on the 12-lead ECG (reflected by leads V1 and V2 only). This is one reason for the imperfect sensitivity and in some cases limited diagnostic accuracy of the traditional 12-lead ECG in patients with structural heart disease. Further development of vectorcardiographic parameters is crucial for improvement of diagnostic and prognostic accuracy of both the ECG and VCG. Determination of the main QRS plane is needed to assess whether the traditional 12-lead ECG is sufficient for individual patient follow-up. In patients with a predominantly horizontal main QRS loop plane, the standard 12-lead ECG may miss critical information, and orthogonal XYZ ECG leads, or a complete VCG may be needed to provide complete information.

Limitations

The small number of patients with post-MI scar is a limitation of this study. Due to a small sample size only univariate comparison between cases and controls was performed. Although sample size was small, we estimated power for all variables as 0.8 with the exception of roundness index. This study was not designed to determine whether observed VCG morphology features are merely characteristics of the presence of post-MI scar, or are specifically associated with the scar-related arrhythmogenic substrate. A larger, prospective study is needed to validate the clinical importance of these VCG morphology descriptors.

Conclusion

VCG QRS loop morphology in patients with infarct-cardiomyopathy, scar, and sustained monomorphic VT is characterized by folding phenomenon, decreased planarity of the QRS loop, increased variability of the dihedral angle across the QRS loop, and the appearance of abrupt irregularities in consecutive dihedral angles (QRS loop folding). Qualitative and quantitative QRS loop morphology descriptors may be useful to identify individuals at risk of sudden cardiac death and should be investigated further in prospective studies. In post-MI patients with VT, the main QRS plane is predominantly horizontal (as compared to frontal in healthy controls), which may make the traditional 12-lead ECG less sensitive in detecting abnormalities of ventricular conduction. A VCG or orthogonal XYZ ECG leads are necessary to determine complete information on electrical propagation in individuals with a predominantly horizontal main QRS plane.

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Highlights

- Frafmented QRS has low sensitivity for detection of QRS loop folding
- Circular statistic of the normal vector of main QRS loop plane is reported
- Value of the dynamic of the dihedral and rotational angles throughout the QRS loop

Figure 1.

Vectorcardiographic QRS loop morphology assessment. **A.** Best fitted (main) plane of the QRS loop. Red lines indicate the QRS vectors passing through the origin of QRS loop. **B.** Measurement of QRS loop roundness. Dotted lines demonstrate QRS vectors forming triangles used to calculate the area of the loop. **C.** Measurement of QRS loop thickness. Two parallel planes encompassing horizontal QRS loop. The distance between these two planes represents the thickness. **D.** Measurement of rotational and dihedral angles. Unit planes are defined between two consecutive samples and QRS origin.

Mean Normal Vector Azimuth
Healthy Group

mean direction -41.8 degrees; vector strength 0.800

Mean Normal Vector Elevation
Healthy Group

mean direction 42.5 degrees; vector strength 0.975

Mean Normal Vector Azimuth
VT Cases Group

mean direction -57.7 degrees; vector strength 0.512

Mean Normal Vector Elevation
VT cases Group

mean direction 30.7 degrees; vector strength 0.963

Figure 2.

A circular raw data plot for normal vector of the main QRS plane azimuth (**A,C**) and elevation (**B,D**) in Healthy Controls (**A, B**) and VT Cases (**C, D**). The length of each spike is proportional to the frequency of that direction. The resultant or mean direction is indicated by an arrow from the centre of the circle with length the radius of the circle reflecting the vector strength.

Figure 3.

The bars represent rotational and dihedral angles calculated over QRS loop in a healthy control (A) and a participant of the VT Cases group (B).

Figure 4.

Representative examples of autocorrelation function plot in a healthy control (A) and a participant of the VT Cases group (B). Red dots represent the values of autocorrelation coefficients at different lags, and horizontal blue lines demonstrate the confidence intervals. [18]

Figure 5.

Representative example of QRS loop folding in a patient with the history of sustained monomorphic ventricular tachycardia. (A) 12-lead ECG. Red circles show presence of notches on fragmented QRS. (B and C) show QRS loop of the same patient from two different views. Notching intervals on ECG were mapped to QRS loop and demonstrated as red segments on the loop.

Figure 6. Representative examples of QRS loop with highest (A, B) and lowest (C, D) planarity indices and their corresponding 12-lead ECG for two different VT patients.

Table 1

Demographic characteristics and Vectorcardiogram morphological parameters for Cases and Controls

Parameter	Healthy (N=81)	VT cases (N=8)	P Value
Age(SD), y	39.0(14.2)	68.0(7.8)	<0.0001
Male gender, n(%)	42(51.8)	3(37.5)	0.439
Roundness index(SD)	0.59±0.23	0.65±0.23	0.681
Planarity index(SD)	0.88±0.10	0.63±0.22	0.014
QRS loop Thickness (SD), μ V	291.76± 133.26	210.59±91.61	0.045
QRS vector magnitude(SD), μ V	2461.0±722.31	841.63±386.68	<0.01
Rotational angle variance, median (IQR), °	11.70 (6.38–20.40)	12.40 (7.37–49.30)	0.561
Rotational angle RMSSD, median (IQR), °	3.24(2.17–4.81)	3.98(2.42–7.87)	0.295
Rotational angle lag-1 ACC [*] (SD), °	0.64±0.21	0.64±0.13	0.960
Rotational angle lag-1/10th QRSd ACC (SD), °	−0.02±0.13	0.04±0.07	0.089
Dihedral angle variance, median (IQR), °	542 (343–773)	897 (575–1450)	0.029
Dihedral angle RMSSD (SD), °	35.11±13.07	47.65±12.66	0.027
Dihedral angle lag-1 ACC [*] (SD), °	0.49±0.14	0.49±0.14	0.985
Dihedral angle lag-1/10th QRSd ACC [*] (SD), °	−0.08±0.11	0.12±0.12	0.002

* ACC=Autocorrelation coefficient. QRSd=QRS duration

Table 2

Circular statistic: comparison of the main loop normal vectors and QRS vectors

Circular variable	Healthy (n=81)	VT Cases (n=8)	P
Normal vector azimuth, mean(95% CI), °	-41.8(-57.7 to -49.2)	-57.7(-51 to 130)	<0.05 [‡] [§]
Mean Normal vector azimuth strength	0.800	0.512	
Mean Normal vector azimuth range, °	254.0	180.6	
Absolute Azimuth of Main Plane Normal, mean(95% CI), °	66.8(62.1-71.5)	36.7(18.6-54.9)	<0.05 [‡] [§]
Normal vector elevation, mean(95% CI), °	42.5(39.7-45.3)	30.7(19.6-41.8)	NS [‡] [§]
Mean Normal vector elevation strength	0.975	0.963	
Mean Normal vector elevation range, °	68.2	49.8	
QRS vector azimuth, mean(95% CI), °	30.9(22.7 to 39.1)	-77.2 (-35.7 to -118.8)	<0.001 [‡] [§]
Mean QRS vector azimuth strength	0.778	0.655	
Mean QRS vector azimuth range, °	286.0	144.4	
QRS vector elevation, mean (95% CI), °	49.4(45.5-53.3)	56.3(27.6-85.0)	<0.05 [‡] [§]
Mean QRS vector elevation strength	0.941	0.734	
Mean QRS vector elevation range, °	135.0	166.5	
Rotational angle, mean (95% CI), °	4.1(3.9-4.4)	3.6(2.4-4.7)	<0.05 [‡] [§]
Mean rotational angle strength	1.0	1.0	
Mean rotational angle range, °	7.7	4.8	
Dihedral angle, mean(95% CI), °	20.4(19.1-21.6)	27.8(21.6-34.0)	<0.05 [‡] [§]
Mean dihedral angle strength	0.955	0.988	
Mean dihedral angle range, °	29.2	30.7	

[‡]Watson U-square statistic;[§]Kuiper statistics;

Table 3

Comparison of folding on QRS loop and notching on 12-lead ECG in VT cases

		QRS loop folding on VCG	
		Present (+)	Absent (–)
Fragmented QRS complex on 12-lead ECG	Present (+)	15 (8 meet fQRS criteria; 3 on non-contiguous leads; 4 on a single ECG lead)	4 (notch on a single ECG lead)
	Absent (–)	11	0

fQRS = fragmented QRS