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Modeling Vectorcardiograms Based on LV Papillary Muscle Position

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Abstract

Background—Vectorcardiographic QRS loops illustrate the electrical activation of the left ventricle (LV) in three dimensional space; however, the individual variability in these loops is not well understood. The left bundle branch fan distributes the initial activation to the LV and has been shown to distribute its fascicles between the LV papillary muscles. Computer models of LV activation utilizing papillary muscle as the initial electrical activation points accurately predict QRS duration and frontal plane axis.

Methods—12 healthy adults received standard 12-lead ECGs and 1.5 T cardiac MRI. Software developed by ECG-TECH Corp generated 3 dimensional QRS vector loops for each subject. Short and long axis papillary muscle positions were measured for each subject using cardiac MRI images. A theoretical plane equidistant from the endocardial origins of each papillary muscle was constructed. Vectors perpendicular to the QRS vector loop and the theoretical plane termed the “plane identifier” were used for comparison. Spearman-rank correlation was used to compare the azimuth and elevation of the “plane identifiers” of the QRS vector loop and the theoretical plane.

Results—No correlation was found between the azimuth or elevation of the theoretical plane and the QRS vector loops with Spearman-rank correlation coefficients of $\rho = 0.11$ ($p=0.71$) and $\rho = 0.22$ ($p=0.49$) respectively. Subgroup analysis by QRS vector loop morphology (planar vs. non-planar; narrow vs. wide) also demonstrated no correlation.

Conclusions—Modeling the activation of the LV based on papillary muscle position alone may be overly simplistic. Better understanding of what other factors contribute to individual variation in LV activation will help develop a more useful theoretical model.

Introduction

Vectorcardiographic QRS loops illustrate the electrical activation of the left ventricle (LV) in three dimensional space; however, the morphology of these loops varies widely among

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healthy individuals.¹ Previously developed models of LV activation based on the orientation of the heart in the thorax alone have failed to explain the variability in the morphology of the QRS vector loop.² However, it is known that LV activation is dependent on the distribution of the rapidly conducting left bundle branch (LBB) fan. This fan is anatomically bounded by its anterior and posterior fascicles which terminate in the endocardial origins of the LV papillary muscles.⁴ There is considerable anatomic variation in the position of the LV papillary muscles and, subsequently, the LBB fan in patients without cardiac structural pathology. Despite this variability, groups of anterior and posterior fibers within the LBB fan project towards the anterior and posterior LV papillary muscles as previously described by Rosenbaum et al.⁶ Durrer et al. note that the initial activation points of the LV are consistently found in three regions: an area on the anterior paraseptal wall, a central area on the left surface of the intraventricular septum and an area on the posterior paraseptal wall.³ These regions are consistent with the areas over which the LBB fan commonly distributes. While previous studies have shown that in healthy hearts, the QRS vector loop lies in a single plane; previous models of this loop have not accounted for the variation in the structure of the LV conduction system to predict the position of this plane.⁷

A computer model of the three dimensional vectorcardiogram was originally developed by Solomon and Selvester⁸ and later modified by Olson et al⁷ which uses the papillary muscle positions as landmarks indicating the borders of the LBB fan and distributes points of initial electrical activation between these borders to simulate the electrical current carried by the LBB fibers. This model generates planar QRS vector loops that bisect and lie perpendicular to a hypothetical line between the endocardial bases of the anterior and posterior papillary muscles (Figure 1). We hypothesize that this phenomenon also occurs in physiologic activation. The initial activation of the LV is determined by the LBB fan which is also distributed between these two landmarks, and the purkinje network conducts the electricity from these points at an equal rate in all directions. This symmetrical activation would result in a mean electrical vector loop running nearly equidistant from these landmarks throughout ventricular systole.

Previous work by Hakacova et al. has shown that modeling the activation of the LV in this manner provides accurate predictions of both the QRS duration and frontal plane axis in healthy adults. These studies demonstrate that if more of the endocardium was activated by the LBB fan (as evidenced by papillary muscles more distant from the intraventricular septum), the QRS duration was shorter. They also found that the asymmetry in the papillary muscle position was predictive of the frontal plane axis.⁹ This study illustrates that papillary muscle positions can influence electrocardiographic parameters of the QRS complex.

This study evaluated the ability of this modeling technique to predict the measured position of the planar QRS vector loop as measured from the electrocardiogram (ECG) in three dimensional space. More accurate representations of the activation pattern of the LV will improve the prognostic and diagnostic utility of this model. We hypothesized that the theoretical plane equidistant from the endocardial origins of the papillary muscles would demonstrate significant agreement with the measured position of the plane of the QRS vector loop derived from measured electrocardiograms (ECGs).

Methods

Study population

This study utilized data collected for a previous study examining the relationship between papillary muscle position and QRS complex characteristics from 16 healthy adult volunteers from Glasgow, UK without a known history of cardiac disease, lung disease nor ECG or magnetic resonance imaging (MRI) data suggesting prior myocardial infarction, right

bundle-branch block or left bundle-branch block.¹⁰ Of these 16 subjects, 12 were included in this study. 2 were excluded for presence of left ventricular hypertrophy and 2 were excluded for missing ECG or MRI data.

Data collection

Demographic information including gender, age, weight, height and medical history were collected by one of the co-investigators of the previously described study.¹⁰ Descriptive statistics are reported as means $\pm$ standard deviations.

ECG and MRI

All subjects had standard 12-lead ECG recordings obtained as previously described⁹ and had their ECGs electronically stored in a Megacare ECG management system (VF 2.1, Drager, Germany). This electronic data was converted by the Dower transformation to x, y, z coordinates and mapped into the three dimensional space using vectorcardiogram software developed by ECG-TECH Corp to generate the QRS vector loop for each subject. The planar QRS vector loop is constructed by determining the instantaneous QRS vector at 2 ms intervals and connecting the termini of these vectors to form a closed loop. A vector lying perpendicular to the plane of the QRS vector loop termed the “plane identifier” was calculated for each subject by averaging the cross-products (using x, y, z body coordinates) of sequential vector pairs at 2 ms intervals. The direction of this vector was determined by the right hand rule.

MRI data was collected using a 1.5-T cardiac MRI scanner and 5 mm thick short axis images as previously described.⁹ The positions of the anterior and posterior papillary muscle groups were determined independently as previously described by Hakacova et al. Briefly, to determine the short axis position of the papillary muscles we used cine images of the short axis to distinguish the papillary muscles from the endocardial trabeculae and measured the relative positions of the most septal portion of each papillary muscle group in relation to the intraventricular septum (Figure 2). Long axis position was determined by measuring the distance from the short axis image containing the most septal/basal portion of each papillary muscle to the base of the heart. These measurements were performed by two of the investigators (N.H. and Z.L.) and all papillary muscles positions were agreed upon.

Determining the theoretical plane

The theoretical plane was determined by software developed by ECG-TECH Corp (Huntington, NY).⁷ The short axis position of each papillary muscle was measured as described above and entered into the software. The position of the heart in the chest was taken into account by adjusting the long and short axis of the model in accordance with each subject's heart. The long axis orientation of the LV was estimated by the cross product of the DICOM vectors in the MRI short axis views. The rotation of the heart about the long axis was estimated by measuring the x, y and z coordinates of the line bisecting the intraventricular septum as seen in the short axis.

A line between the most septal portions of each papillary muscle was constructed for each subject and a theoretical plane was generated that bisects and lies perpendicular to this connecting line creating a surface that is equidistant from each papillary muscle. A vector lying perpendicular to this theoretical plane originating from the O point and oriented anterosuperiorly (termed the “plane identifier” for the theoretical plane) was generated for comparison with the plane identifier of the QRS vector loop.

Data analysis

The large amount of variation in both papillary muscle position and QRS vector loop positions were not anticipated to follow a Gaussian distribution and thus non-parametric analysis was performed. Spearman-Rank correlation coefficients were calculated to determine the correlation between the azimuth and elevation of the “plane identifiers” of both the theoretical plane and the QRS vector loop.

Subgroups were identified based on the shape and planarity of the QRS vector loops. Subjects were subjectively grouped into “planar” vs. “non-planar” with the hypothesis that the “planar” group’s findings were in keeping with the symmetrical activation assumption and thus would be more accurately predicted by the theoretical plane. The subjects were also subjectively grouped into “long/narrow” vs. “short/wide.” A computer model that created QRS vector loops based on papillary muscle position consistently generated loops that lacked the large apical forces that created narrow loop morphologies in many patients; thus, we hypothesized that the “short/wide” group may be better predicted by the theoretical plane. Two sided significance was adjusted from $\alpha = 0.05$ to $\alpha = 0.017$ using the Bonferroni adjustment for these two additional hypotheses.

Results

Study Population

Twelve health subjects (6 men and 6 women) were included in this study. The mean age of subjects was 28 ± 11 years and the mean weight was 71 ± 9.7 kg. The “plane identifiers” for the QRS vector loops had a mean azimuth of $29.58 \pm 24.02^\circ$ and a mean elevation of $54.08 \pm 8.90^\circ$.

Correlation between theoretical plane and QRS vector loop

Analysis of the overall group showed no significant correlation between the azimuth or the elevation of the theoretical plane and QRS vector loops. Spearman-Rank correlation coefficients for the azimuth and elevation were $\rho = 0.11$ ($p=0.71$) and $\rho = 0.22$ ($p=0.49$) respectively (Figure 3). Subgroup analysis also did not reveal any significant correlation between the predicted and measured azimuths or elevations for any of the four subgroups (data not shown).

Subgroup analysis

We looked back over the subjects individually to see where the loops fit well to our simulations and where they did not. By comparing the theoretical planes and the QRS vector loops side-by-side, we can learn more about the strengths and weaknesses of the model.

“Planar” vs. “Non-planar”—Figure 4A illustrates a subject whose QRS vector loop appears very planar. Panel A1 shows how well the theoretical plane predicts the location of the QRS vector loop. Panel A2 illustrates how when the QRS vector loop is viewed on edge for this patient, it coincides with a single plane. The plane identifiers are shown for both the theoretical plane (green arrow) and the measured VCG loop (yellow arrow). The theoretical plane appears to be angled more inferiorly than the QRS vector loop. Comparison of the “plane identifiers” in this subject showed a difference in azimuth of 1.3° and a difference in elevation of 22.73° . This subject is an example of someone in whom we expected to be able to predict the location of the QRS vector loop well with the theoretical plane; however, the agreement was much stronger for the azimuth than for the elevation and as a group, subjects with “planar” loops did not demonstrate significant agreement with the theoretical plane.

Figure 4B shows a subject whose QRS vector loop showed agreement with the predicted plane for the early and late vectors but not for the middle vectors. Panel B1 shows the relationship between the vector loop and the theoretical plane. Panel B2 shows the QRS vector loop on edge and how it does not adhere to a single plane. The “plane identifiers” for the theoretical plane and the QRS vector loop appear to be quite discordant. Comparison of this VCG loop’s “plane identifier” to that of the hypothetical plane showed one of the worst agreements of the group (44.7° difference in azimuth and 16.2° difference in elevation). As we anticipated, this subject’s non-planar QRS vector loop was poorly estimated by our hypothesis that assumes symmetrical activation.

“Long/narrow” vs. “Short/wide”—Figure 4C shows a subject with a QRS vector loop that is long and narrow. The vectors representing the mid-QRS forces are large and point towards the apex of the heart. Both the overhead view of Panel C1 and the edge view of Panel C2 show how the QRS vector loop seems to intermittently intersect with the theoretical plane. Comparing the location of the “plane identifiers” demonstrate a difference in azimuth of 24.2° and a difference in elevation of 16.2°. The magnitude of these differences was very close the average difference for the total population (23.0° difference in azimuth and 14.0° difference in elevation) suggesting this subject is representative of the group as a whole.

An example of a more blunted and wide QRS vector loop is shown in figure 4D. The QRS vector loop for this subject does not have the same long vectors pointing towards the apex in the middle of the QRS complex and is more similar in morphology to the vector loops generated by computer simulations utilizing the assumptions of symmetrical activation. The overhead (Panel D1) and edge views (Panel D2) of the QRS vector loop show that close agreement between these two structures as well as the similarity in the angle of the “plane identifiers.” Comparison of the location of the “plane identifiers” reveals a difference in azimuth of 4.0° and a difference in elevation of 5.0° which was one of the best agreements for the overall group. It should be noted that as a group, patients with “short/wide” QRS vector loops did not show significant agreement with the theoretical plane.

Discussion

Overall, this model was not able to predict the location of the QRS vector loop in the overall sample or any of our derived subgroups. It should be noted that although we artificially divided the group into “planar” and “non-planar” groups, all of the QRS vector loops demonstrated a high degree of planarity with standard deviations from the plane 72.45 μ V. The relative planarity of all of the QRS vector loops is consistent with our assumption that the activation of the LV occurs in a symmetrical fashion; however, we were unable to predict the location of the QRS vector loop from the papillary muscle positions. The small sample size of this study also limited our statistical power and the likelihood of observing statistically significant findings.

This model assumes that the initial activation forces are equally distributed between the two papillary muscles. Dissections by Demoulin et al. have demonstrated that there is a large amount of variation in how the LBB fan distributes its fascicles.⁵ Imbalance in the size and number of anterior and posterior fascicles would result in a QRS vector loop that differed from the theoretical plane and may be a source of variability.

Additional factors that we have not yet accounted for in this model may also have played a role in the variability of QRS loop position. Modeling the activation of the LV as a symmetric process defined by two points may be overly simplistic and more complex modeling techniques may be required. Factors such as imbalances in wall thickness may

cause asymmetrical electrical activity and non-planar QRS vector loops. As we learn about additional factors that influence the activation sequence of the LV, we will incorporate them into this model.

The positions of the papillary muscles in both the long and short axis were determined by finding the point at the most septal portion of the papillary muscle inserted into the wall of the LV. These measurements have a subjective component and may be imprecise. The papillary muscles divide into smaller branches before inserting into the LV making the identification of these structures difficult. Higher resolution MR images and better 2 and 4 chamber, long axis view images may improve the precision of these measurements in the future. It may also be more accurate to model the initial activation at the midpoint of the papillary muscle endocardial insertion points rather than the most septal portion. It should be noted, however, that measurements obtained using similar methods were used in a model that was found to be predictive of QRS duration and frontal plane axis suggesting that this technique is valid.⁹

Another limitation of our method is our reliance on left ventricular anatomical structures without accounting for right ventricular (RV) structure. While the QRS vector loops are largely dependent on forces within the more massive LV, these loops represent the sum of electrical activity in both the LV and the RV. Differences in RV structure and size may have been an important factor in predicting the location and morphology of QRS vector loops. Subjects included in the present study did not have right ventricular hypertrophy (RVH) or right bundle branch block (RBBB); however, accounting for the anatomic variation in RV structure may allow for more accurate predictions of the features of the QRS vector loops. Further study of subjects with and without RBBB may allow for better understanding of how the RV activation affects the QRS vector loops.

Although the results of this study are negative, understanding the extent to which different factors influence the characteristics of the vectorcardiogram is essential to developing a more complete model of LV activation. The development of this theoretical model will help further the understanding of factors that contribute to the cardiac activation patterns observed in individuals without pathology. This knowledge will augment clinicians' abilities in diagnosing and recognizing abnormal patterns as well as better understand how pathologic processes affect cardiac electrophysiology. Being able to predict normal electrophysiology based on anatomy may help future clinicians better identify pathology in uncertain situations. Eventually it may be possible to compare "true" and "simulated" QRS vector loops to distinguish pathologic patterns from normal variation to aid clinical decision making.

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Figure 1. Simulated QRS vector loops bisecting the plane between the papillary muscles
 Panel A: Left ventricle of the heart showing the initial excitation and the summation vector falling in line with the plane bisecting the papillary muscles.
 Panel B: Left and right ventricles at the initial excitation. The left ventricle is windowed to allow a view of the papillary muscles. The small black arrows represent the dipole vectors for each local region and the large yellow summation vector is the vector sum of the small vectors. The planar character is due to the balancing of forces on each side of the plane.

Figure 2. Short axis measurements for determining papillary muscle position

To determine the position of each papillary muscle 6 points were defined by each individual's anatomy. W1 and W2 are the insertion points for the right ventricle and were used to find the midpoint of the intraventricular septum (S). A line perpendicular to the midpoint of the septum to the LV free wall (line SF) was constructed. The papillary muscle location was measured by the angle between the most septal portion of each papillary muscle (P1 and P2) and line SF.

Figure 3. Correlation of azimuth and elevation

Scatter plots demonstrating the lack of correlation between the azimuth (left panel) and elevation (right panel) of the “plane identifier” for the theoretical plane (x-axes) and the azimuth and elevation of the “plane identifier” for the QRS vector loop (y-axes) for the 12 study subjects.

Figure 4. 3D renderings of QRS vector loops, theoretical planes and “plane identifiers”
 QRS vector loops are represented in 3 dimensional space by colored vectors with magnitude and direction reflective of the mean electrical activation at 2 ms sequential intervals (progressing in order from red, blue, green and finally to pink). These vector loops are also projected onto the frontal, horizontal and sagittal planes and the 12-lead ECG recordings used to derive these loops are also presented in their orderly sequences. The theoretical loop is depicted in light pink. The “plane identifiers” for the QRS vector loop are depicted by the large yellow arrows; whereas, the “plane identifier” for the theoretical plane is shown by the large green arrow. Panels on the left show an overhead view and panels on the right view the loops from the edge of the QRS vector loop. Row A depicts the “planar” group, row B the “non-planar” group, row C the “long/narrow” group and row C the “short/wide” group.