Vector Analysis of Atrial Activity from Surface ECGs Recorded During Atrial Fibrillation

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Abstract

The traditional perception of atrial fibrillation (AF) as having random and disorganized electrical activity has begun to fade over recent years. Studies involving intra-cardiac mapping have shown evidence of an underlying spatial and temporal organization in the atria during AF.

In this study, we used a modified QRS-T cancellation method for multi-lead ECGs and examined vectorcardiograms synthesized from twenty 12-lead ECGs recorded during AF. As a preliminary study we also analyzed ECG recordings taken during an ablation procedure of a typical atrial flutter patient where mechanisms and activation sequences were well known.

Of the twenty synthesized vectorcardiograms of AF, five showed a consistent cyclical vector sequence. The other recordings often showed segments of repeated sequences lasting two or three f-wave cycles.

1. Introduction

The traditional perception of atrial fibrillation (AF) as having random and disorganized electrical activity has begun to fade over recent years. Studies involving intra-cardiac mapping have shown evidence of both an underlying spatial and temporal organization in the atria during AF [1-3]. Gerstenfeld et al. demonstrated with the use of an orthogonal catheter the presence of transient "linking", the tendency for wave fronts to follow paths of previous excitation [3]. Furthermore, it has become increasingly evident that fibrillatory waves (f-waves) seen in the surface electrocardiogram (ECG) during AF contain physiologic information related to the mechanisms in the atria and also suggest some degree of organization. For example, spectral analysis of the AF signal in the ECG has shown that a distinct peak exists in the 4 to 9 Hz region [4]. This spectral information correlated with atrial rates derived from simultaneous intra-atrial recordings [5,7]. In addition, changes in the spectrum was used to track drug effects [6-7].

Many AF studies, such as those involving atrial rates and f-wave amplitudes and morphology, have focused on lead V1 of the 12-lead ECG due to V1's comparatively high atrial-to-ventricular amplitude ratio, which is commonly thought to be attributed to the proximity of the uni-polar lead to the right atrium. However, the prevalent theory that AF consists of multiple circulating wave fronts [8] and recent evidence that AF often arises from the left atrium [9] suggests that multi-dimensional information should exist in the 12-lead ECG. Ventricular signals (and even P-waves during sinus rhythm) have long been thought of as three-dimensional signals. There is no reason why f-waves should be thought of any differently. If spatial organization exists in the atria during AF, the f-waves in multi-lead ECG recordings of should reflect that.

Because of the f-waves' lack of clear features in the scalar ECG, in contrast to defined QRS, P or T-waves, we attempted to examine the three-dimensionality of AF from the vectorcardiogram (VCG). In this study, we used a modified QRS-T cancellation method designed for multi-lead ECGs and examined VCGs synthesized from twenty 12-lead surface ECGs recorded during AF. As a preliminary study to test the ability of the synthesized VCG (SVCG) to distinguish several known atrial activation sequences and mechanisms, we also analyzed ECG recordings taken both before and after an ablation procedure of a typical atrial flutter including pacing at known sites.

2. VCGs synthesized from 12-lead ECGs

Vectorcardiographic analysis helps to visualize the three dimensionality of the electrical activity of the heart. It is considered superior to the scalar ECG in the detection of atrial enlargement, ventricular hypertrophy, and myocardial infarction [10]. However the rarity of the Frank orthogonal leads system in clinical use necessitates the ability to construct the VCG from the more standard 12-lead system. The inverse Dower matrix has been shown to be an effective transformation from the 12-lead to Frank-lead system [11,12] and thus was used in this study.

3. Vector analysis during an atrial flutter ablation procedure

To demonstrate the ability of the SVCG to distinguish different activation sequences of the atria, we chose to examine atrial activity recorded during different phases of an ablation procedure where the activation sequences were well known. The patient was a 72-year-old male diagnosed with typical atrial flutter. Simultaneous intra-cardiac and surface ECG signals were recorded at a 977 Hz sample rate with a Prucka CardioLab EP System, (GE Medical Systems, Milwaukee, WI, USA).

The reentry circuit of typical flutter in the right atrium has been well established [13] and was verified in this procedure from intra-cardiac mapping. The general pattern is counterclockwise circular (Figure 1), going up the atrial septum (and passively to the left atrium), and down the right atrial anterior wall. The interior boundary consists of the superior and inferior vena cavae (SVC and IVC), the coronary sinus (CS), and a line of functional block along the crista terminalis extending between the SVC and IVC. An area of slow conduction in the low septal right atrium has been shown.

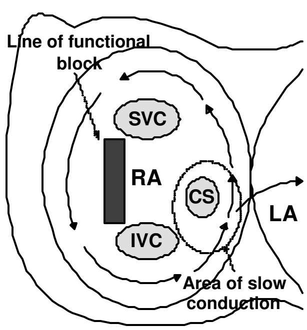

Figure 1. Left anterior diagram of the right atrium viewed through the tricuspid valve and the counterclockwise reentrant path of typical flutter. Major landmarks of the circuit include the superior and inferior vena cava (SVC and IVC), coronary sinus (CS), and line of functional block along the crista terminalis.

Flutter waves before the ablation were isolated in time from the QRS and T waves during 4:1 conduction. The SVCG of the flutter waves (Figure 2A) showed a counterclockwise loop with a faster downward velocity and slower initial upward velocity consistent with the expected activation sequence of typical flutter [14,15]. It is important to keep in mind that the VCG illustrates only the sequence of the magnitude and direction of the spatial vector and does not reflect where the activations are in the anatomy.

The patient was ablated in the narrow isthmus between the inferior vena cava and the tricuspid ring and sinus rhythm was restored. This isthmus has been shown to be a necessary path in the circuit for typical flutter [16]. The sinus P loop is shown in Figure 2B. To determine the success of the ablation, conduction through the isthmus is tested by pacing from the proximal CS and from the low lateral right atrium. Conduction block in the isthmus would require an activation initiating at the CS to travel up the septum and around the SVC to reach the low lateral right atrium. Similarly, an activation initiating in the low right atrium must travel up the lateral wall around the SVC and then down to reach the CS.

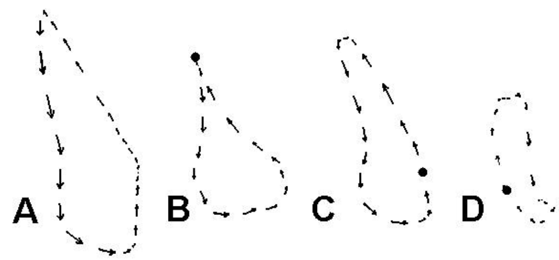

Figure 2. 45° left-anterior oblique view of the SVCG loop of atrial activity during A) typical atrial flutter, B) post-ablation sinus rhythm, C) post-ablation coronary sinus pacing, and D) post-ablation low lateral right atrium pacing. The black dots in B, C, and D mark the P-wave onsets and offsets (not applicable for flutter).

Figure 2C shows the vector loop of the P wave during CS pacing. The counterclockwise sequence of this P loop can be seen to be similar to the pre-ablation flutter loop in Figure 2A. Rosen et al. had previously demonstrated that rapid pacing in the CS could mimic flutter waves in the ECG [17]. Pacing in the low lateral right atrium produced a clockwise loop (Figure 2D) as expected.

The analysis of the SVCG during the ablation procedure of an atrial flutter patient demonstrates the ability to reflect different activation sequences in a way that is intuitive from a physiological standpoint.

4. Vector analysis of atrial fibrillation

4.1. Isolation of atrial activity in the ECG

The main obstacle in the ECG analysis of AF is the isolation of atrial activity from ventricular activity. Slocum et al. introduced “mean /median beat subtraction” (MBS) as a method that has remained a staple in the analysis of f-waves [4,18]. This method takes advantage of the regular morphology of the QRS-complexes and T-waves and their lack of correlation to the atrial activity during AF. A template created from the mean or median QRS-T signal is subtracted from the original signal. The result will be the isolated f-waves as the remainder.

Stridh and Sornmo recognized that respiration, body movement, and other factors might shift the electrical axis affecting both the morphology and scaling of the QRS-T waveforms from beat to beat and cause transfers of information from lead to lead [19]. This, combined with a low atrial-to-ventricular signal ratio, often results in poor subtraction in precordial leads V3 through V6. Poorly subtracted QRS and T-waves can leave residuals that can overwhelm the f-waves in the subtracted signal.

Because the effectiveness of the SVCG depends on the quality of the subtraction, we have developed the method of "principal component subtraction" (PCS) as an attempt to improve QRS-T subtraction in the ECG beyond leads II and V1. PCS compensates for electrical axis shifts by operating in the principal component domain. First, the three components of highest variance are selected from the Karhunen-Loeve (K-L) transformed median beats. These three orthogonal components including an original beat of a particular lead to be subtracted are K-L transformed again. The resulting three principal components of this transform are used to reconstruct an estimate of the QRS-T portion of the original beat. Performance improves when QRS and T-waves are operated on separately.

4.2. Data analysis

Twenty ECGs taken for routine clinical purposes and demonstrating AF were retrieved from a Marquette MUSE[tm] digital ECG system (GE Medical Systems, Milwaukee, WI, USA) at the cardiac graphics laboratory at Evanston Hospital. The ECGs selected were shown to have coarse AF with f-waves visible in all leads. The signals were free of premature ventricular contractions and excessive baseline wander, muscle noise, or motion artifacts. The 12-lead ECGs were ten seconds in length and sampled at 250 Hz. After performing the PCS algorithm, the signals were bandpass filtered with cutoff frequencies of 1 and 50 Hz. The peak frequencies of the subtracted signals in lead V1 ranged from 5.1 to 8.1 Hz with mean 6.7 + 0.8 Hz. The SVCG of the subtracted signal was then analyzed in the frontal, left sagittal, and transverse planes to observe if a primarily clockwise or counterclockwise activation sequence could be detected in each plane. Analysis of ECG recordings was approved by the Institutional Review Board of Evanston Northwestern Healthcare.

4.3. Results

Of the twenty ECGs, five showed consistent loop-like patterns through most of the ten-second segment. An example, illustrated in Figure 3, shows a two second ECG segment of one of these five ECGs along with its corresponding SVCG. A clockwise component is evident in the left sagittal and transverse plane. Although this AF appears to be fairly organized, the morphology and rate changes seen in the ECG are clearly more indicative of AF than flutter. The bottom of Figure 3 shows the vector angle in the left sagittal plane plotted against time. The Z-axis is considered zero-degrees with the angle increasing clockwise. Due to the clockwise action in the left sagittal plane, the vector angles show a fairly constant increases over time. The 360-degree cycles also can also be seen to correspond with the ECG f-wave cycles.

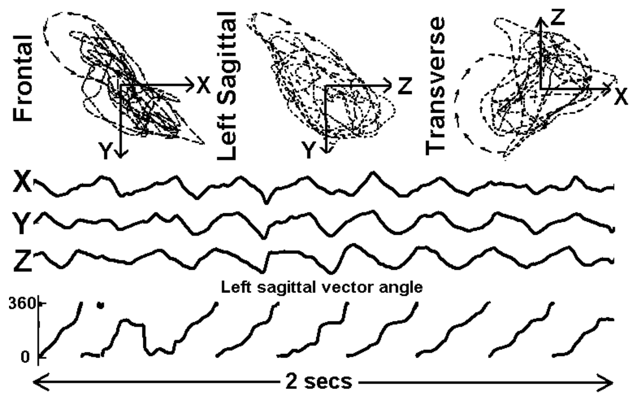

Figure 3. SVCGs of two seconds of coarse AF with the corresponding synthesized XYZ-lead subtracted ECG. The positive X, Y, and Z-axes point left, inferiorly, and posteriorly, respectively. The bottom of the figure shows the vector angles in the left sagittal plane plotted against time.

Although fifteen of the twenty ECGs did not show a consistent pattern in the SVCG, these recordings often had several patterns repeated over a few f-wave cycles. Some even had alternating clockwise and counterclockwise loops. Only two of the recordings did not have any apparent repeated vector patterns.

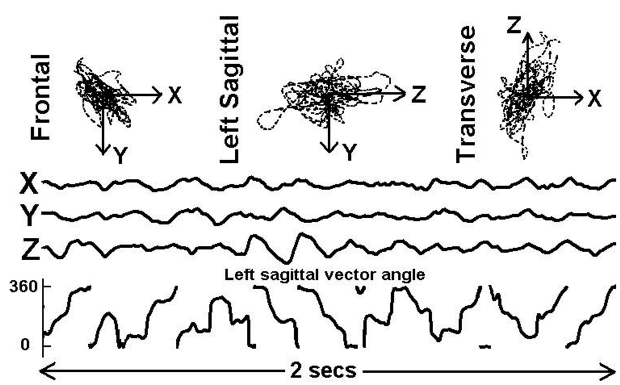

Figure 4. Second example of a SVCG.

Figure 4 displays signals of a patient where the ECG and SVCG show a seemingly less organized AF. The plot of the vector angle in the left sagittal plane consists of both repeating and alternating sequences of clockwise and counterclockwise activations. Interestingly, the 360-degree cycles still correspond to the ECG f-wave cycles.

5. Discussion

The results from this initial examination of f-wave vectors appear to be consistent with the results of Gerstenfeld et al. demonstrating linking in AF. However, in order to relate the patterns seen in the SVCG to actual mechanisms in the atria, a better understanding of the pathophysiology of AF is required. Nevertheless, the vector loops show that the three-dimensionality of electrical activation in which QRS, P or T-waves are commonly described can be also applied to atrial activity during both flutter and fibrillation.

While PCS worked well in most cases in isolating atrial activity in the ECG, some distortion of f-waves did occur. Enhancements in QRS-T subtraction would further aid in the analysis of the SVCG.

Although the inverse Dower matrix has been shown to be a good approximation in the conversion from the 12-lead to the Frank-lead ECG for QRS loops, it has not been tested for atrial activity. Further examples of the performance of this method for well-known activation sequences, such as those during the ablation procedure, are required before relying on it to analyze AF.

6. Conclusions

Vector analysis of atrial activity during AF and flutter was shown to aid visualization of spatial activation patterns better than from scalar 12-lead ECGs alone. Additional studies may include the development of pattern recognition and classification of vector sequences as well as comparison to intra-cardiac mapping of the atria. The ability to classify AF based on spatial as well as spectral properties may lead to a better understanding of AF mechanisms and thus improvements in management.

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