Isointegral Analysis of Body Surface Maps: Surface Distribution and Temporal Variability in Normal Subjects

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SUMMARY  Isointegral analysis of body surface potential maps has been proposed as a useful approach to data reduction. To determine the normal magnitude and surface distribution of a series of time-integral measurements, we acquired body surface potential maps from 40 men and 15 women, ages 20–46 years, who were clinically normal. In a subset of 16 subjects, variability in serial maps was assessed as the root-mean-square difference in time-integral values between maps using the same electrode application (recordings separated by 15 minutes) as well as when different electrode applications were required (recordings separated by 1–7 days).

Isointegral maps of the QRS, ST-T, QST, ST-segment and Q-zone time integrals all demonstrated predominantly bipolar body surface distributions, with positive values located over the precordium and negative values over the right chest and back. Men had significantly (p < 0.05) greater maximum and minimum values than women for all time integrals except Q zone. Variability in serial maps was small and was significantly greater (p < 0.001) between maps acquired with different, compared to the same, electrode application. Moreover, variability tended to be greatest for time integrals that reflected repolarization events. We conclude that time-integral analysis of body surface potential mapping is a practical method for data reduction that holds considerable promise as a technique to rapidly assess the ECG effects of many drugs and interventions. Variability in sequential maps is small but must be considered before serial alterations in time integrals are accepted as meaningful.

BODY SURFACE POTENTIAL MAPPING (BSPM) offers considerable promise as a method that allows more comprehensive and regionally discriminative analysis of electrocardiographic information than is possible with standard ECG methods. A major problem with BSPM techniques, however, is the difficulty in developing a practical means of analyzing and displaying the enormous quantity of data generated. To achieve efficient data reduction, we have adopted a technique based on the measurement of time integrals from each of the body surface ECG signals, with the data displayed in the form of isointegral contour maps. This approach to BSPM analysis has also been advocated by Abildskov and coworkers, although the concept of time integration over the entire QRST complex was first introduced into electrocardiography by Wilson et al. in 1934.

In this study we established the normal magnitude, surface distribution and temporal variability of a series of ECG time integrals. These data are necessary if BSPM is to be effective in clinical studies, particularly those designed to detect changes during dynamic states or secondary to pharmacologic intervention.

Subjects and Methods

Forty men and 15 women, ages 20–46 years, were studied. None had a history of cardiovascular disease and all were normal on physical and 12-lead ECG examination.

Recording

Our system of recording the ECG signals has been described. Briefly, ECG signals from 117 torso (fig. 1) and three limb electrode sites are sampled simultaneously and the data are recorded in digital format with Wilson's central terminal as reference. This system, based on a Varian V72 computer, has a resolution of 10 µV, in the dynamic range ± 5 mV, with a sampling frequency of 500 samples/sec/channel. For this study, each recording session consisted of 15 seconds of continuous data acquisition, spanning several respiratory cycles.

Processing

The ECG signals are processed off-line on a general-purpose computer (Xerox Sigma 5) using a system of ECG analysis programs developed at our institution. The programs perform selective averaging of P-QRS-T complexes from each lead; ectopic beats

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and artifacts are rejected and linear baseline drift is corrected. All measurements of ECG time integrals are made from these averaged complexes at time instants determined from edited Frank X, Y and Z leads (fig. 2). About 16 beats were averaged during any 15-second recording session.

Five time integrals were evaluated: QRS, ST-T, QRST, Q-zone and ST segment. The QRS time integral was calculated for each lead as the algebraic sum of all potentials from the time instant of QRS onset to QRS offset multiplied by the sampling interval. This represents the net area under the curve using the PR interval as baseline. The ST-T time integral was similarly calculated from the time instant of QRS offset to T offset; the QRST time integral thus represented the algebraic sum of the QRS and ST-T time integrals. In addition, the Q-zone time integral was calculated from QRS onset to the midpoint of the QRS complex and the ST-segment time integral from the onset to the end of the 3/8 portion of the ST-T segment. All time integrals were expressed as μV/sec.

Display

The map format for ECG time integrals is illustrated in figures 3 and 4. Each rectangular area represents the torso, with the left side reflecting the front and the right side the back; thus both the left and right margins represent the right midaxillary line. Each contour line within the rectangle connects points of equal time-integral value. The solid lines indicate positive time-integral values and the interrupted lines negative values. Between the solid and interrupted lines lies the zone of near-zero time-integral values. Both the positive and negative isointegral lines extend from this near-zero zone in a logarithmic progression, with each decade numerically identified. The maximum and minimum time-integral values are indicated on each map. In addition to plotting maps of all time integrals for each subject, maps were also constructed from the group mean value at each lead site.

Study Protocol

Each subject had at least one map acquired while in a resting state. In addition, a subgroup of 16 subjects (14 males and two females) had four sequential maps
acquired to assess temporal variability. Two of the sequential maps, separated by 15 minutes, were recorded on day 1, a third on day 2 and a fourth on day 7. The two maps on day 1 were acquired with the same electrode application and were designated T1 and T2. The maps acquired on day 2 and day 7 each required reapplication of electrodes and were designated T3 and T4, respectively.

Temporal variability in the magnitude of the various time integrals was quantified by deriving a

Figure 3. Mean isointegral plots from 40 males and 15 females for each of the time integrals. These maps were constructed from the group mean time-integral value at each electrode site. The numerals represent the mean values for maximum and minimum time integrals. See Methods for detailed description of map-display format.
root mean square of the intermap, time-integral differences according to the formula

$$V = \sqrt{\frac{\sum_{i=1}^{n}(X_{T2} - X_{T1})^2}{N}}$$

where V represents variability (in μV/sec) X refers to the actual time-integral value at a given lead site, T2 and T1 refer to map acquisition times, and N refers to the number of lead sites. Variability for each time integral was calculated for T2 − T1 and T3 or T4 − T1 in each subject.

Statistical analysis was by t test for paired and unpaired observations.

Results

Mean QRS, ST-T, QRST, ST and Q-zone isointegral maps are illustrated in figure 3. Both males and females demonstrated smooth bipolar surface distributions for all time integrals, with positive values located over the precordium and negative values over the right chest and back. Although maps from individual subjects reflected some variation, there was a marked consistency in the spatial distribution of the various time integrals. These maps show the spatial concordance of depolarization events (as represented by the QRS and Q-zone time integral) and repolarization events (as represented by the ST-T, ST and QRST time integrals).

The only significant difference in maps from male compared with female subjects was the data range between maximum and minimum integral values (table 1). Except for the Q-zone time integral, the peak positive values were significantly (p < 0.05) higher and the peak negative values significantly lower for males than for females.

Temporal Variability

Magnitude changes in the time integrals during sequential recordings are illustrated in figure 5. There was a small but measurable intermap variability in the magnitude of all time integrals, both between maps acquired with the same, and with separate, electrode
TABLE 1. Data Range of Time Integrals in 55 Normal Subjects

<table>
<thead>
<tr>
<th>Time integral</th>
<th>Male (n = 40)</th>
<th>Female (n = 15)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum (µV·sec)</td>
<td>Minimum (µV·sec)</td>
</tr>
<tr>
<td>QRS</td>
<td>48 ± 22*</td>
<td>-50 ± 21*</td>
</tr>
<tr>
<td>STE-T</td>
<td>139 ± 37*</td>
<td>-49 ± 15*</td>
</tr>
<tr>
<td>QRST</td>
<td>147 ± 49*</td>
<td>-70 ± 17*</td>
</tr>
<tr>
<td>ST</td>
<td>35 ± 11*</td>
<td>-10 ± 3*</td>
</tr>
<tr>
<td>Q zone</td>
<td>36 ± 11*</td>
<td>-19 ± 9</td>
</tr>
</tbody>
</table>

Values are mean ± sd.
*p < 0.05 compared with corresponding value in females.

applications. Variation was significantly (p < 0.001) greater, however, between maps acquired with separate electrode applications compared with those obtained during the same recording session. Also, the degree of variability in the magnitude of the ST-T and QRST time integrals (reflecting repolarization events) was greater than that of the QRS time integral (reflecting depolarization events). In physiologic terms, this variation in the magnitude of the five time integrals was small. Thus, when expressed as a percentage of the respective mean data range for normal males (table 1), T2 - T1 variability averaged only 3.5% (range 2.4-5%), compared with 7.2% (range 6-9%) for T3 - T1.

Figure 5. Mean variability in magnitude of time integrals in 16 subjects. The cross-hatched bars represent the mean variability between maps acquired with the same electrode application (T2 - T1). The open bars reflect mean variability between maps acquired with separate electrode applications (T3 - T1). The vertical line at the top of each bar represents the standard deviation. For all time integrals, there was significantly less (p < 0.001) variability between maps acquired with the same, compared to a separate, electrode application.

Temporal variability in the surface distribution of the isointegral contours was not quantified. However, visual inspection of sequential maps in these normal subjects revealed little identifiable alteration, even when maps were compared from different electrode applications.

Representative examples of temporal variability in QRS and ST-T time integrals are shown in figure 4.

Discussion

Many studies have demonstrated the increased information content from surface mapping techniques compared with standard electrocardiography. To date, most investigators have used the isopotential analysis technique, with maps being generated at numerous time instants throughout the cardiac cycle. This approach allows detailed analysis of sequential changes in ECG potentials throughout the cardiac cycle, although the enormous data mass makes display cumbersome and the assessment of serial records time-consuming.

We believe that time-integral analysis, with display as isointegral maps, holds considerable promise. Despite the small number of maps per cardiac cycle, much of the spatial information available from the more detailed isopotential approach is maintained. Also, time-integral analysis offers a rapid means of identifying portions of the QRST complex that are abnormal or have undergone change secondary to a specific intervention. Once identified, such segments may then be subjected to more detailed (instant-by-instant) analysis. Finally, the isointegral approach may best allow detection of abnormalities or alterations in those portions of the electrical cycle in which potential changes are small or occur gradually over long periods, such as the ST-T and T-P segments. By the same reasoning, however, isointegral analysis would not be expected to be as sensitive as the isopotential method in detecting abnormalities or alterations in segments, such as the QRS complex, in which potential change is great and occurs rapidly. It follows, therefore, that time-integral analysis offers promise as a complementary rather than an alternative approach for assessing body surface maps.

Our results show that normal subjects have relatively consistent torso distributions for each of the
five time integrals assessed. The fact that each time integral has a very similar surface distribution makes even relatively minor abnormalities readily apparent to an experienced observer. This has been our experience in studies in which we have used isointegral maps to assess patients with persistent ST-segment elevation after anterior infarction and to assess electrical evolution during the early phases of acute myocardial infarction.

Although the torso distribution of each time integral was not different between males and females, the range of integral values was significantly different. Men had significantly greater maximum and minimum values. We do not know why this is so, but it may reflect a greater cardiac mass in male subjects. This observation indicates the need for greater awareness of sex-related differences in electrocardiographic measurements.

The variability in time-integral magnitudes in the sequential maps in this study is an important consideration when this technique is used to assess map alterations secondary to the passage of time or as a result of planned intervention. We detected a small but measurable variability even when map acquisition was separated by only 15 minutes, using the same electrode application and with the subject at rest in a standard position. The greatest variability occurred in time integrals that reflected repolarization events (ST-T and QT) but was also apparent in the QRS and Q-Zone measurements. The source of this variability is not completely clear. Although respiration may cause changes in the cardiac position and be associated with rhythmic variations in several ECG measurements, this would not be expected to account for the intermap variability in our study because we recorded and averaged complexes over several full respiratory cycles at each recording session.

The variability in time-integral magnitudes between maps obtained on different days was significantly greater (p < 0.001) for all time integrals than when the maps were acquired at the same recording session. This is not surprising, because even minor changes in positioning of the electrode columns would be expected to result in some alteration in the recorded signal. Thus, technical factors may largely explain this greater variability. However, that there was again proportionately greater variability in the time integrals reflecting repolarization compared with depolarization suggests that biologic factors are accounting for at least some of the change. Despite these temporal alterations in the magnitude of the time integrals, there was very little variation in the spatial distribution of the isointegral plots in these normal subjects. Although alterations in surface distribution may well be more important than magnitude changes, further studies are required to determine the electrophysiologic significance and diagnostic reliability of specific time integral patterns.

The QRS time integral evaluated in this study has recently become the subject of renewed interest. In 1934, Wilson et al. hypothesized that the algebraic sum of the QRS area reflected intrinsic repolarization properties, which are independent of ventricular activation sequence. Abildskov et al. presented support for this hypothesis by demonstrating that changes in QRST area were directly proportional to changes in local refractory periods. This work lends support to the suggestion that QRST time-integral maps may reflect regional disparity of primary ventricular recovery properties and may, therefore, be a useful method to detect states of increased vulnerability to dysrhythmia. Our normal subjects generally displayed smooth dipolar distributions of QRST time integrals, suggesting that there is normally a relative homogeneity of ventricular recovery properties. Whether future studies will confirm the usefulness of this measurement in the detection of dysrhythmia-vulnerable states (and perhaps as a means to assess efficacy of antidysrhythmic therapy) remains to be established.

We conclude that the time-integral analysis approach to body surface mapping is a practical method for data reduction and holds considerable promise as a means to rapidly assess the electrocardiographic effects of a host of drugs and interventions. Temporal variability in both the magnitude and spatial distribution of the time integrals is normally small and probably reflects both biologic and methodologic factors; however, this must be considered before serial alterations in isointegral maps are accepted as meaningful.

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References
Body Surface Detection of Delayed Depolarizations in Patients with Recurrent Ventricular Tachycardia and Left Ventricular Aneurysm

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SUMMARY In eight patients with chronic ventricular tachycardia and left ventricular aneurysms, we detected delayed ECG wave forms after the QRS complex from the body surface using a high-resolution ECG recorder, amplification and signal averaging. Delayed wave-form activity (D wave) extended a mean of 70 msec beyond the termination of the QRS complex. This delayed activity frequently extended to the limit of the recording window, and may thus continue throughout much of diastole. Antiarrhythmic agents never abolished the delayed activity; however, it was abolished by aneurysmectomy in four patients. Ventricular tachycardia did not recur after surgery in the four patients during a mean follow-up of 1 year. The D wave was not found in eight control patients who had chronic recurrent ventricular tachycardia nor in 11 of 12 who had aneurysms alone. The surface D wave can be readily and reproducibly detected by high-resolution electrocardiography and appears to be specific for patients with left ventricular aneurysms who also have chronic recurrent ventricular tachycardia. This delayed wave-form activity has been noted during catheter and surgical endocardial and epicardial mapping. It may represent persistence of the cardiac impulse in islands of myocardium and may be a manifestation of the delayed and fractionated activity, noted by previous investigators.

HIGH-RESOLUTION electrocardiography has been in existence for over 8 years as pioneered by three research groups: Berbari et al.,15-16 Flowers et al.,6,14 and Stopczyk et al.11,12 However, technical limitations prevented widespread clinical application of signal averaging and amplification. Recent advances in electronics have made high-resolution recordings clinically feasible.5,18

In 1978, Berbari et al.14 detected discrete multiphasic wave forms appearing during the ST segment of a surface-averaged lead in experimental canine myocardial infarction. They postulated that these waves represented areas of myocardium that showed marked delay in activation. This activity derived from a very small total mass compared with the entire ventricular mass, thus explaining why such delayed activity had been undetectable by routine standard-gain surface electrocardiography.14 By appropriate noise filtration, amplification and signal averaging, these low-level signals, which were frequently in the microvolt range, could be recorded. These techniques were applied to the same canine model in the same laboratory in which El-Sherif et al.18,16 found that delayed and fractionated activity extended beyond the T wave and was associated with the onset of ventricular arrhythmias. Although similar slow, fragmented and delayed activity has been observed in experimental animals,17,18 not until the endocardial mapping studies of Josephson et al.19-22 and Horowitz et al.23 in patients with recurrent ventricular tachycardia (VT)
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