Interpretation of Isopotential Surface Maps in Patients with Ostium Primum and Secundum Atrial Defects

By Richard B. Karsh, M.D., Madison S. Spach, M.D., and Roger C. Barr, Ph.D.

SUMMARY
The purpose of this study was to determine if there were consistent differentiating patterns in body surface potential maps in children with normal hearts and in those with ostium primum versus ostium secundum atrial septal defects. A second purpose was to interpret the isopotential surface maps in terms of the position of intracardiac electrical wave fronts.

Body surface activity throughout QRS demonstrated three major intervals: developing, transitional, and declining potentials. Patients with both types of atrial septal defects demonstrated complex distributions (multiple maxima) during the transitional interval which were not encountered in normal subjects. In the primum group, the distribution of positive and negative potentials sequentially changed in an inverted pattern as compared to the pattern in those patients with secundum defects. Furthermore, during the transitional interval the potential distribution was considerably more complex in the primum group. In two additional patients, body surface maps were helpful in clarifying misleading and atypical conventional electrocardiograms.

The presence of simultaneous multiple maxima could only be accounted for by the existence of multiple wave fronts simultaneously present within the heart. In particular the emergence of two widely separated anterior chest maxima in patients with secundum atrial defect indicated the simultaneous presence of prominent left and right ventricular wave fronts. Also, the marked differences in the relative positions of the major body surface maximum and minimum could be accounted for only by considerable differences in the position and extent of intracardiac wave fronts. For example, the target distribution, consisting of an isolated minimum surrounded by multiple maxima and positive potentials over the upper body, in the ostium primum patients, indicated epicardial breakthrough in a wave front positioned in the anterosuperior portion of the heart. In contrast, normal subjects and patients with secundum defect had distributions indicating antero-inferior wave front position at the time of right ventricular epicardial breakthrough.

Additional Indexing Words:
Intracardiac electrical wave fronts

Presentation of body surface potential distributions (body surface maps) provides a picture of cardiac electrical events as projected on the body surface. Surface maps differ from selective scalar leads by providing an integrated picture containing more information for predictions concerning single or multiple intracardiac wave fronts than is available from viewing scalar leads alone. From an electrophysiologic point of view, an

From the Department of Pediatrics and Division of Biomedical Engineering, Duke University, Durham, North Carolina.
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Address for reprints: Madison S. Spach, M.D., Department of Pediatrics, Duke University, Durham, North Carolina 27706.
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advantage of surface maps is the apparent association of areas of positive and negative surface potentials with major wave fronts within the heart. While significant advances are being made by direct cardiac measurements of the human heart, developing conceptual models in various entities from surface events remains worthwhile since considerable time will be necessary to overcome the limitations of extensive direct exploration of the human heart.

This report presents the sequential surface maps during QRS in children with normal hearts, secundum atrial defects, and ostium primum atrial defects. A comparison of these three conditions seemed worthwhile because of considerable clinical interest and because of the well-known abnormality of the conduction system which programs ventricular excitation in an abnormal fashion in ostium primum defects. This report, concerning surface maps, is intended to extend the previous concepts of the wave fronts in the heart and their relation to the electrical events on the body surface.

### Methods

#### Patient Population

Table 1 summarizes the diagnostic categories and hemodynamic data of the different groups undergoing study. The 22 normal children were judged to have normal hearts on the basis of auscultation, electrocardiograms, and chest x-rays. All patients with secundum atrial defect had the diagnosis confirmed at cardiac catheterization and at surgery. Left ventricular angiocardiograms in the 10 patients with ostium primum atrial defects demonstrated the typical abnormal chamber configuration of endocardial cushion defects as described by Baron and associates. Finally, two additional special patients were studied in whom we interpreted the ECG as being atypical for the underlying diagnosis. One had an ostium primum defect with the typical left ventricular chamber deformity by angiocardiography (diagnosis confirmed at surgery); the ECG was considered to be consistent with a secundum rather than a primum atrial defect. The second was a child with a pulmonic ejection murmur, and the electrocardiogram demonstrated left axis deviation (ostium primum defect). Cardiac catheterization revealed a normal hemodynamic state, and angiocardiography showed a normal left ventricular chamber configuration.

#### Electrocardiographic Methods

Conventional ECGs were obtained in all patients and, except for the two special patients, were considered to be typical for the assigned diagnostic category and hemodynamic state. The procedure for recording and constructing isopotential surface maps has been reported in detail previously. In summary, 150 electrocardiograms were recorded from the upper part of the chest, the abdomen, and the back, five points at a time simultaneously with a reference lead. All beats chosen for analysis occurred during resting expiration. These data were then processed by an IBM 360/75 computer following A-D conversion. Isopotential surface maps were produced for every millisecond during QRS. The maps were reviewed to determine whether consistent characteristic patterns were demonstrated by the patients within each different diagnostic category. Because differentiating patterns were evident from the analysis, the results will be presented by demonstrating selected distributions at various instants throughout ventricular activation in individual patients, which were considered to illustrate the characteristic features of each diagnostic group.

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**Table 1**

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>No. of patients</th>
<th>Age (yr)</th>
<th>L-R shunt (%)</th>
<th>RV peak pressure (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normals</td>
<td>22</td>
<td>3-15</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Secundum ASD</td>
<td>11</td>
<td>4-13</td>
<td>52-70</td>
<td>25-50</td>
</tr>
<tr>
<td>Primum ASD</td>
<td>10</td>
<td>3-12</td>
<td>50-65</td>
<td>30-60</td>
</tr>
</tbody>
</table>

Additional special patients

1. Final diagnosis: Primum ASD with ECG suggestive of secundum ASD
   - No. of patients: 6
   - Age (yr): 55
   - RV peak pressure (mm Hg): 30

2. Final diagnosis: Normal with ECG suggestive of endocardial cushion defect
   - No. of patients: 11
   - Age (yr): 0
   - RV peak pressure (mm Hg): 25
Prediction of Cardiac Wavefronts

Since the isopotential surface maps were so different from one patient group to another, it seemed reasonable to estimate where cardiac wavefronts might be to account for the potential distributions on the surface as they developed in time throughout QRS. Predictions of cardiac wavefronts from specific surface distributions at various instants of time had to be consistent with results from previous studies in humans with normal hearts\(^5\)\(^,\)\(^4\) and with secundum defects\(^3\) and endocardial cushion abnormalities.\(^1\) Although our procedure was intuitive, the principal considerations were the known heart position and anatomy, the geometry of the maxima and minima on the body surface, and the instant of time within QRS. The initial wavefront predicted during the first 10 msec of QRS primarily was based on the direct myocardial studies of Scher and Young\(^8\) and Boineau and co-workers\(^9\) in dogs and Durrer\(^4\) and Blumenschein and associates\(^8\) in humans. Estimates for the subsequent instants of time emphasized continuity with the evolving wavefronts from the initiating site of activation.

Results

Body Surface Potential Distributions

Body surface potential distributions are usually characterized in terms of maxima (highest potentials) and minima (lowest potentials). Frequently the maps have "pseudopods," which are irregular protrusions of the contour lines from the areas of the maxima or minima. For each map, the line designated as 0 millivolts represents the average voltage over the body surface for that instant of time.

In most patients, during QRS the overall voltage magnitudes rise to a peak and then decline. While the voltage magnitudes are high, alterations in voltage distributions are usually rapid. In analogy to the Q, R, and S approach to standard ECG interpretation, the potential distributions in the various diagnostic categories were subdivided into developing, transition, and declining intervals for comparison.

The format of the presentation of the body surface isopotential surface maps is shown in figure 1. The vertical edges of the map represent the body surface area of the region which joins the right side of the back to the right axillary region. Thus, one half of the map represents the anterior and lateral portions of the chest, and the other half of the map represents the back region.

Normal Child

The developing interval was characterized by the onset of a maximum on the anterior central chest with the minimum in the left axillary region or back (fig. 1 at 7 msec). As the maximum increased in intensity, the minimum shifted to the right shoulder region (18 msec). The transitional period began at 21 msec in the normal child, which was shown with the sudden appearance of a minimum over the sternum while the right shoulder minimum persisted. These two minima were transiently separated by an area of potentials at a higher level (21 msec). This distribution has previously been related to specific intracardiac events, namely, the arrival of the major wavefront of the right ventricle at the epicardial surface.\(^7\)\(^,\)\(^10\) The distribution continued to change with rapid coalescence of the two minima to assume a position over the central sternum while the anterior chest maximum continued to increase in intensity and shifted over the left precordial region (31 msec). The total distribution at this time was characterized by positive potentials occupying the lower part of the thorax, while negative potentials enveloped the remainder of the thorax, except for the extension of the maximum over the left precordial region. Thereafter, the maximum migrated around the left axillary region to assume a position over the central back (38 msec). The declining period was characterized by the distribution shown at 50 msec with a maximum in the back, a V-shaped negative potential region anteriorly, and a minimum over the sternum.

Patients with Secundum Atrial Septal Defects

The 12-lead electrocardiograms (fig. 2) and the corresponding sequence of surface maps (fig. 3) of two patients are presented. During the developing interval, the potential distribution and sequential changes were similar to normal. It was during the transitional period that the major divergence from normality was
Figure 1
initiated. This consisted of the development on the anterior chest of two maxima and an interposed minimum (fig. 3, I-34 msec and II-29 msec). Subsequently the left chest maximum disappeared, rather than continue its movement throughout QRS as in the normals. Also, as the left chest maximum disappeared, the right chest maximum became more prominent. Declining distribution in all patients with secundum atrial defects consisted of a maximum on the right upper chest beneath the clavicle and a minimum nearby over the precordium.

Patients with Ostium Primum Atrial Septal Defects

All patients in this group had routine 12-lead electrocardiograms which were characteristic of the ostium primum defect,11 as shown for two patients in figure 4. In a general sense, the surface map patterns throughout QRS (fig. 5) occurred with an inverted distribution compared to those for both normal children and patients with secundum atrial defects. The developing interval was initiated by a maximum positioned anteriorly but more inferiorly than in the two other groups. Additionally, there was a broad base of positive potentials extending inferiorly around the torso, which was not found except in this group (fig. 5, I-10 msec and II-10 msec). Thereafter, the inferior maximum migrated superiorly toward the left shoulder. The transitional period was initiated in a different fashion from that in the normal and secundum atrial defect groups. The broad base of positive potentials positioned inferiorly began to constrict toward the anterior central chest with these changes progressing further to the development of negative potentials or a minimum over the inferior part of the mapped surface (fig. 5, I-34 msec and II-39 msec). The initial invasion of negative potentials from the inferior part of the surface mapped showed as an inverted direction from that in the other two groups; for in these groups the negative potentials on the upper chest initiated the transitional period by invading the area of positive potentials from a superior direction.

Another prominent feature of the primum group was the subsequent rapid emergence of an isolated minimum over the central or left anterior chest. This minimum was positioned amid multiple maxima and produced what will be referred to as a “target” distribution (fig. 5, I-43 msec and II-44 msec).

As the transitional interval continued, two types of patterns were noted. In one the left chest maximum diminished as the right chest maxima became more intense (fig. 5, I-43, 47, and 54 msec). Concomitantly, the target minimum increased with coalescence of the inferior minimum into the anterior central chest region (I-54 msec). This produced a continued inverted distribution with positive potentials oriented superiorly and negative

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Normal sequence of QRS body surface potential distributions. (I) The rectangle superimposed on the drawing of the body surface torso shows the format used for presenting the isopotential surface maps. Since both the front and the back of the thorax are represented on each map, the anterior chest is represented by the left half of the map and the back is represented by the right half of the map. The solid circles represent the relative positions on the map of the conventional precordial leads (V₁ to V₅₅).

(II) The sequence of QRS maps shown is that of a 7-year-old normal boy. The developing interval was characterized by the rapid development of an anterior sternal maximum and posterior minimum (7 msec). As the maximum continued to increase in intensity, the minimum shifted to the right shoulder (18 msec). Suddenly an isolated sternal minimum developed (21 msec) to initiate the transitional period. This resulted in the presence of two minima separated by an area of higher potential on the right anterior chest (“saddle distribution” as defined by Taccardi10). As the minima coalesced to form a single prominent central sternal minimum, the maximum continued to increase while it shifted over the left precordium (31 msec). The left precordial maximum then migrated around the left axillary region to the central back (38 msec). The declining interval consisted of a posterior maximum with positive potentials over the back while negative potentials enveloped the anterior chest with a V-shaped demarcation line (50 msec).

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Electrocardiograms from patients with secundum atrial defects. The electrocardiograms shown were recorded in patients whose corresponding isopotential surface maps are presented in figure 3.

(I) This electrocardiogram was recorded from a 6-year-old child whose left-to-right shunt comprised 55% of pulmonary blood flow. The right ventricular peak systolic pressure was 28 mm Hg. Note that lead V1 demonstrates an rS configuration.

(II) This electrocardiogram was obtained from an 8-year-old child with a secundum atrial defect and a left-to-right shunt of 65% of pulmonary blood flow. The right ventricular peak systolic pressure was 33 mm Hg. Note the typical rsR' configuration in lead V1, in addition to the right axis deviation.
potentials oriented inferiorly. The second pattern encountered during the late transitional interval was that of accentuation of the target minimum with maxima positioned over the right and left anterior parts of the chest (fig. 5, II-48 msec). This was associated with the inferiorly developing positive potentials in association with the gradual diminution of the left precordial maxima (II-53 msec). The left precordial maximum in these patients differed from the secundum and normal groups in that it showed no migration leftward around the left axilla before it disappeared; rather, it tended to migrate superiorly toward the left shoulder and disappear.

The declining interval in all patients consisted of a maximum over the right upper chest with a closely adjacent midsternal minimum. The terminal distribution appeared quite similar to that in patients with secundum atrial septal defects.

Additional Special Patients

Incorrect Clinical Diagnosis of Type of Atrial Defect. Figure 6 illustrates the 12-lead electrocardiogram and sequence of surface maps in a 6-year-old child whose x-rays demonstrated moderate cardiomegaly and increased pulmonary vascular markings. Auscultation revealed a pulmonic ejection murmur, constant splitting of the second sound, and diastolic rumble along the lower part of the sternum. There was no systolic murmur at the apex. The electrocardiogram and the Frank vectorcardiogram were consistent with an ostium secundum defect, right axis deviation, and clockwise rotation of the QRS loop in the frontal plane. At cardiac catheterization the presence of an atrial septal defect was confirmed and the shape of the left ventricle was found to be consistent with the typical geometry of an ostium primum defect. There was no evidence of mitral insufficiency. The catheterization findings were subsequently confirmed at surgery. The child, in fact, had an ostium primum atrial septal defect without mitral insufficiency.

In general, this patient's surface maps appeared to be transitional between those of the groups with the ostium secundum and the ostium primum atrial septal defects. During the developing interval, the distributions appeared compatible with the normal or secundum groups and did not demonstrate the inferiorly positioned maximum or inferior base of potentials typical of the primum group. However, during the transitional interval a prominent target distribution developed with isolated minimum positioned amid maxima over the anterior chest—a finding which was characteristic only of the ostium primum group. The remaining portion of the transitional interval consisted of the presence of two prominent maxima, one over the left precordium and the other over the right anterior chest, with an interposed minimum. The left chest maximum gradually disappeared while the one on the right increased and migrated to the upper right chest.

Misleading Interpretations of Electrocardiogram of a Normal Child. The electrocardiogram and sequential body surface maps shown in figure 7 are those of an 11-year-old lad who was seen initially because of a prominent pulmonic ejection murmur. X-rays revealed questionable increased pulmonary vascular markings and questionable cardiac enlargement. The electrocardiogram was felt to be consistent with an ostium primum defect primarily on the basis of left axis deviation, although there was no evidence of right ventricular hypertrophy. Cardiac catheterization was carried out to clarify the diagnosis. This revealed normal right heart pressures and the absence of intercardiac shunting. The left heart angiocardiogram revealed a left ventricle of normal configuration. The final diagnosis was that of a normal child with an abnormal sequence of ventricular excitation, possibly due to a defect in conduction through the superior branch of the left bundle.

The isopotential surface maps were different from any of those encountered in the ostium primum defect group. The developing interval (fig. 7, II-10 and 22 msec) was characterized by the onset of an anterior chest maximum positioned normally. The sequential changes continued in a normal manner throughout QRS, rather than demonstrating...
Figure 3

Typical QRS isopotential surface maps of patients with secundum atrial defects. (I) This sequence of maps corresponds to the electrocardiogram shown in figure 2, I. The developing interval appeared to be similar to normal (3-16 msec). The onset of the transitional period was also similar to normal with the appearance of a central sternal minimum (26 msec). Rapidly, thereafter, as the central sternal minimum enlarged, a pseudopod of positive potentials emerged over the right lower chest anteriorly (31 msec) and this subsequently resulted in the presence of two prominent anterior chest maxima with an interposed minima (34 msec). During the declining interval the left precordial maxima disappeared, rather than migrate around the left axillary region to the back while the right chest maxima enlarged and migrated to the right upper chest (54 msec).
any of the specific features encountered in the ostium primum group; in other words, during the transitional period, no inferiorly positioned minimum, no target distribution, and no evidence of prominent bilateral chest maxima developed. In summary, the maps were consistent with those of the normal group.

**Predicted Cardiac Events as Interpreted from the Surface Maps**

**Normal Child**

Four instants of time depicted in the isopotential surface maps of the normal child in figure 1 were used to predict the cardiac wave fronts for the corresponding instants of time. The corresponding predictions are shown in figure 8. At 7 msec the prominent feature of the map was the anteroposterior relationship of the maximum and the minimum. This can be accounted for by an enlarging wave front invading the left ventricular septal and apical regions, as previously shown in animals. The salient feature of the potential distribution in figure 1 at 18 msec was the increasing left precordial maximum and right shoulder minimum. To account for the tilt between the maximum and the minimum, the three dimensional representation (fig. 8, 18 msec) of the intracardiac wave front shows an enlarged wave front produced by coalescing excitation of the lateral and diaphragmatic portion of the left ventricle and the paraseptal region of the right ventricle. As represented here, the total wave front assumes an ellipsoidal shape which, in reference to the body surface, tilts slightly downward and to the left.

The most complex distribution for the normal child is shown in figure 1 at 21 msec which demonstrates a left precordial maximum and the sudden appearance of a central sternal minimum. The central minimum is separated from another minimum at the right shoulder by an interposed region of higher potential, the "saddle distribution" as described initially by Taccardi for normal adults. To account for this complexity, the wave front within the heart (fig. 8, 21 msec) requires two major features: a major wave front positioned somewhat similar to the previous wave front shown at 18 msec (left precordial maximum and right shoulder minimum), and a hole in the anterior surface of the total wave front produced by right ventricular breakthrough (fig. 8, 21 msec). The timing of right ventricular breakthrough and arrival of wave fronts in the free wall at the epicardial surface are consistent with the thinness of the normal right ventricle.

The genesis of this distribution was originally predicted by Taccardi, and subsequently confirmed by Spach and co-workers to be related to RV breakthrough.

At 31 msec in figure 1 the potential distribution had changed to that of a left axillary maximum, prominent central sternal minimum, and a general distribution with positive potentials inferiorly and negative potentials superiorly. This can be accounted for by a wave front similar to that shown in figure 8 at 31 msec. The wave front located in the left ventricle accounts for the position of the maximum and minimum over the precordium; excitation of the diaphragmatic portion

(II) This sequence of maps is for the child whose electrocardiogram is shown in figure 2, II. The developing interval was similar to normal (5-12 msec). The transitional period was initiated in an abnormal fashion; in other words, an upper chest minimum shifted downward over the left precordium into the area of positive potentials (26 msec). Rapidly, thereafter, two prominent maxima developed over the anterior chest with an interposed minimum (29 msec). The left precordial maximum disappeared rapidly rather than migrate around to the back, while the right anterior chest maximum increased (37 msec) and shifted to the area adjacent to the suprasternal notch (58 msec).

Note that the general body surface potential distributions during the transitional period were similar; both developed two anterior chest maxima. This occurred although lead \( V_7 \) showed different curves for the two patients. This difference can be accounted for by the position of lead \( V_7 \) and the movement of the right anterior chest maximum into or around this position.
Figure 4

Typical electrocardiograms in patients with ostium primum atrial septal defects. (I) This electrocardiogram was obtained from a 6-year-old child with an ostium primum defect with mild mitral insufficiency, a left-to-right shunt which comprised 60% of pulmonary blood flow, and a peak right ventricular pressure of 34 mm Hg. Note the typical features of left axis deviation, prolonged P-R interval of 0.20 sec, and the rsR' complex in lead V1. The body surface potential distribution for this patient is shown in figure 5, I.

(II) This ECG was obtained from an 8-year-old child with an ostium primum defect with...
of the ventricles is accounted for by the general horizontal demarcation between the areas of inferior positive and superior negative potentials. Additionally, the juxtaposition of the maximum and minimum with associated steep gradients of potential strongly suggests that the boundary of the left ventricular wave front was positioned close to the high gradient surface area.

Secundum Atrial Septal Defect

Because the potential distributions were similar to normal in these patients until the time of right ventricular breakthrough, only two instants have been used to predict cardiac excitation wave fronts as shown in figure 9. These predictions were derived from the patient's maps shown in figure 3, II. For the two instants shown for this patient, the predicted cardiac events were based partly on previous epicardial excitation studies performed in another group of children with right ventricular hypertrophy.3

In the secundum defect patients, the presence and position of two maxima shown during the transitional interval at 29 msec in figure 3, II were the typical findings when the left-to-right shunt comprised more than 60% of pulmonary blood flow. None of these patients developed a normal saddle distribution of two minima associated with right ventricular breakthrough; rather they developed two distinct maxima. Their presence and position indicated that the right-sided maximum was due to the right ventricle and the left precordial maximum was due to the left ventricle. This is schematized in figure 9 at 29 msec. The general position of the wave front is somewhat similar to normal; however, due to the enlarged right ventricle, the right ventricular free wall wave front occupies a greater area than normal.

The surface distribution shown in figure 3, II at 37 msec has two important features, namely, the absence of a left ventricular maximum and the presence of a right chest maximum with a juxtaposed minimum. In secundum defect patients, the left ventricular maximum disappeared prematurely as compared to normals and, therefore, the distribution shown in figure 3, II at 37 msec is accounted for primarily by a single prominent wave front in the right ventricular free wall3 as shown in figure 9 at 37 msec. The juxtaposition of the right anterior chest maximum and minimum results primarily from the proximity of the right ventricular wave front to the chest surface.

Ostium Primum Atrial Defect

The potential distributions for four instants of time shown in figure 5, I were used to estimate the intracardiac wave fronts shown in figure 10. During initial QRS, the abnormally low position of the anterior maximum shown in figure 5, I at 10 msec is accounted for by the initial wave front being positioned in the diaphragmatic portion of the left ventricle1 as illustrated in figure 10 at 10 msec. The initiation of ventricular activation at this abnormal site can be accounted for by the abnormal course of the bundle of His which results in primary arborization of the left bundle branch on the diaphragmatic surface of the left ventricle as shown by the histologic studies of Lev13 and by iodine studies in the intact heart by Spach and associates.5

The unusual feature of the body surface potential distribution at 34 msec (fig. 5, I) was that the inferior base of positive potentials had collapsed with the production of an inferior minimum with a maximum positioned above this. The genesis of this distribution is most likely the completion of excitation of a large area of the diaphragmatic surface of the left ventricle (fig. 10, 34 msec). The major wave front thus would be positioned superiorly and open beneath. This contrasts to the normal heart which at an analogous instant of time has an ellipsoidal wave front.

The surface potential distribution at 43 msec (fig. 5, I) was distinctive primarily by

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*moderate mitral insufficiency and a left-to-right shunt which comprised 55% of pulmonary blood flow; right ventricular peak systolic pressure was 30 mm Hg. The corresponding surface maps are presented in figure 5, II.*

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Figure 5
the presence of a target distribution; in other words, the presence of an isolated minimum in the positive potential area which was situated over the upper part of the body. The genesis of this unusual distribution can be accounted for by the three dimensional position of the wave front shown at 43 msec in figure 10. The onset of right ventricular breakthrough produces a hole in the superiorly oriented wave front. Thus, the position of the overall wave front would produce the upper body positive potential distribution and the inferior minimum; the hole produced in the wave front by RV breakthrough would result in the isolated minimum. In the ostium primum patients, the transitional interval demonstrated complex distributions with multiple maxima surrounding the isolated minimum. The mechanism of the genesis of these multiple maxima is unclear. However, those positioned over the left precordium subsequently disappeared with persistence of the maxima over the right anterior chest, as shown in figure 5, I at 54 msec. This distribution can be accounted for by the presence of a wave front extending over the right ventricular free wall, over the outflow tract of the right ventricle, and into the superior portion of the left ventricle (fig. 10, 54 msec).

Discussion

It is well appreciated by cardiologists that a high degree of diagnostic accuracy can be achieved from standard electrocardiograms in differentiating patients with normal hearts, secundum atrial defects, and those with ostium primum abnormalities. The isopotential surface maps demonstrated equally consistent differentiating patterns among these three groups. One of the major differences between normal children and those with secundum or primum atrial defects was the development of a more complex potential distribution in the abnormal group during the transitional interval.

In normal children, the transitional period was characterized by the development of a saddle distribution (fig. 1) at 21 msec over the anterior chest which was followed immediately by a less complicated distribution of a single maximum which migrated leftward around the axillary region. All of the secundum defect patients demonstrated a prominent maximum over the right chest in addition to a left precordial maximum during the transitional interval; subsequently, the left ventricular maximum disappeared prematurely while the right ventricular maximum became augmented. In three patients, the evidence for right ventricular hypertrophy in lead V1 appeared minimal (rS in lead V1, fig. 2, I). However, the surface maps demonstrated a prominent right chest maximum which migrated laterally to the position of lead V1. Thus, the position of lead V1 was such that it failed to sample this activity. In the ostium primum group, the distribution was even more complex during the transitional interval than that encountered in the secundum defect patients. An additional salient feature of the primum group was that the sequential positional changes of the maxima and minima, with accompanying areas of positive and negative potentials, appeared

Typical ostium primum atrial defect isopotential surface maps. (I) These surface maps were recorded from the child whose electrocardiogram is shown in figure 4, I. A commentary of the detailed features of the maps is presented in the text. Three distinguishing features for these patients are illustrated here by the following: (1) During the developing interval the initial anterior maximum is positioned abnormally low. (2) The transitional period is introduced by the sudden development of an inferior minimum (34 msec). (3) The transitional period is additionally characterized by the development of an isolated minimum surrounded by multiple maxima and positive potentials over the upper part of the body producing a target distribution (43 msec).

(II) These maps were recorded from the child whose electrocardiogram is shown in figure 4, II. The detailed features of the maps are presented in the text. They illustrate the salient features of the maps shown in I; however, this child, as well as two additional patients with ostium primum, demonstrated a different pattern during the late transitional period in that the lower portion of the body mapped was occupied by positive potentials.

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Ostium primum atrial defect with electrocardiogram suggesting ostium secundum diagnosis. These data were recorded in a 7-year-old child who was proven at catheterisation and surgery to have an ostium primum atrial defect without mitral insufficiency.

(I) The 12-lead electrocardiogram demonstrated right axis deviation and a rsR' complex in lead V1. This was interpreted as being more consistent with the diagnosis of an ostium secundum rather than primum atrial defect. (II) The details of the changes in QRS iso-

Figure 6
generally to be inverted as compared to those of the secundum patients. Particularly, the transitional interval in ostium primum patients was introduced by the development of negative potentials inferiorly on the torso with accompanying maximum and positive potentials positioned superiorly. This distribution was punctuated by the sudden appearance of an isolated minimum with a complex array of multiple maxima surrounding the isolated minimum. The development of this isolated minimum is thought to be related to the arrival of wave fronts at the epicardial surface of the right ventricle.

In addition to the ostium primum group, five children who had partial or complete forms of atrioventricular hypertension, a condition which usually produces more right ventricular hypertension than is present with ostium primum defects, were studied. The increasing degree of right hypertrophy in these children was associated with augmentation of the intensity of the inferior body minimum during the transitional period with a subsequent change consisting of rapid premature disappearance of the left precordial maximum and augmentation of a singular right chest maximum which moved to the right upper chest. These total body surface potential changes associated with increasing degrees of right ventricular hypertrophy are an interesting counterpart of the well-known clinical finding that the mean QRS axis in endocardial cushion defects is positioned superiorly and tends to rotate toward the right shoulder as the degree of right ventricular hypertension is increased.11

One of the interests of this study was to determine if body surface maps would enhance the diagnostic accuracy in two children for whom clinical interpretation of the routine electrocardiogram and Frank vectorcardiogram had been incorrect. In one child with an ostium primum defect, whose electrocardiogram appeared more consistent with a secundum defect, the surface maps were somewhat disappointing since they did not allow clear delineation of the proper underlying abnormality. However, the surface maps revealed a major feature which was consistent with the primum defect group for a prominent target distribution (isolated minimum with surrounding positive potentials) a finding not encountered in the secundum group, developed during the transitional period. In this child with a primum defect, the absence of an abnormally low-positioned initial QRS maximum, as encountered in the remaining primum patients, suggests that the typical abnormality of the conduction system13 may have been less severe than usual. If this transitional conduction system abnormality existed, it could initiate ventricular excitation on the septal surface, rather than on the diaphragmatic portion of the left ventricle. In turn, initiating excitation at the septal surface would produce a normal initial surface potential distribution. Furthermore, the sequential changes in the development of the wave fronts would produce only transiently similar body surface potential distributions to the characteristic primum surface maps; in other words, the transient target distribution.

In the child who had left axis deviation with a superiorly oriented QRS loop, the heart was shown to be normal by cardiac catheterization and angiocardiography. Interpretation of the pattern changes in the surface maps was clearly more consistent with normal and showed none of the characteristic features encountered in any of the patients with endocardial cushion defects. We interpreted the final diagnosis to be a congenital abnormality of the superior division of the left bundle branch, as defined by Gup and coworkers.12 The absence in this patient of any of the typical features of the ostium primum surface maps strongly suggests that the initial position of intracardiac wave fronts is different in patients with a normal left ventricular
Normal child with electrocardiogram demonstrating left axis deviation. These data were recorded from an 11-year-old boy who was suspected of having an ostium primum atrial defect, but cardiac catheterization demonstrated normal findings.

(1) The electrocardiogram demonstrated left axis deviation with superior orientation of the QRS loop in the frontal plane. There was no evidence of right ventricular hypertrophy.
shape and a conduction disturbance of one of the left bundle-branch divisions from that in patients with ostium primum defects. Consequently, the positions of wave fronts within the heart would be different throughout QRS and would produce different body surface maps as encountered in this study.

The use of isopotential surface maps for interpretation in patients is based on the premise that improved use of the surface information will provide a mechanism for improved physiologic interpretation as compared to conventional tracings. Although it is generally appreciated that an increase in voltage in certain leads provides an index of the degree of hypertrophy of either or both ventricles, it is not possible to interpret a collection of scalar leads directly in terms of simultaneous events within the heart. The fundamental strength of the surface map format is the correspondence of major events within the heart to major events on the body surface. For example, the presence of two widely separated distinct maxima over the anterior chest (fig. 3, II, 29 msec) can be produced only by the simultaneous presence of major wave fronts within the right and left ventricles. Previous epicardial studies indicate that this is actually the case. Thus, study of the geometrical arrangement of single and multiple maxima and minima provides considerable insight into the characteristics of ventricular excitation.

Since a view of the body surface potential distribution allows a direct correlation of major events between heart and body surface, the major problem becomes that of obtaining correct measurements from within the heart to make precise electrophysiologic correlations. Although significant advances in our understanding of cardiac excitation in the human have been provided by direct human excitation measurements, especially by the pioneer work of Durrer, the acquisition of extensive information from various areas of the same heart will continue to be a major problem for some time, especially in regard to precise delineation of the sequence of ventricular excitation in a large number of clinical entities. Therefore, the analysis of sequential changes of the position of maxima and minima on the surface during QRS to develop conceptual models of intracardiac wave front position and distribution should be of considerable physiologic and clinical value.

Although many of the wave fronts represented pictorially were derived from the geometric relationships of body surface maxima and minima, the pictorial wave fronts also represent a composite of existing information derived from direct intracardiac measurements and body surface maps. While the wave fronts presented are unconfirmed, they represent a reasonable extension of existing information and provide a base for future clinical, experimental, and theoretical study.

References


in the precordial leads. (II) Sequential changes in the body surface potential distribution during QRS revealed none of the features consistent with those for the group with the ostium primum atrial defects. In fact, the changes were most consistent with those in the normal group. The major difference from normal was the presence of positive potentials extending over the back to encompass the right shoulder region during the latter portion of QRS (43 msec to end of QRS).
Figure 8

Predicted intracardiac wave fronts based on isopotential surface maps: normal child. The position of the major intracardiac wave fronts for four instants of time during QRS is derived from the body surface distributions at comparable instants of time for the normal child shown in figure 1. Thus, the wave fronts depicted for each time instant are directly associated with the surface distributions shown at the corresponding instant in figure 1. To depict the three-dimensional aspects of the intracardiac wave fronts, five separate views are given for each time instant. Each view represents the intracardiac wave front as it would be projected on each side of a box which was folded around the heart. The shaded areas represent the source side of the wave front as viewed for each specific projection, whereas the clear area of the wave front represents a view of the sink side of the wave front for any one projection. For the initial wave front (A) the cross-hatched area indicates the source side of the wave front within the ventricular septum. For the remaining instants of time, wave fronts within the ventricular septum have been ignored and are not included. The dotted lines at the boundary of the wave front signify boundaries within.
Predicted intracardiac wave fronts for secundum atrial septal defect patients. The predicted wave fronts shown for the two instants above were based on the body surface potential distributions shown for corresponding instants in figure 3, I at 29-37 msec. Since the body surface potential distributions were similar to normal during the first half of QRS, predictions were made only for instants thereafter. The conventions used for the presentation of the wave front are similar to those of figure 8. The basis for the above predictions is detailed in the text.

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Prediction of intracardiac wave fronts in ostium primum atrial defect patients. The predicted wave fronts shown above are based on the body surface potential distributions for the corresponding instants in figure 5, I. The convention used for the figures is similar to that of figure 8. Note that the major predicted differences from normals and from secundum atrial defect patients consist of (1) the initiation of ventricular excitation at an abnormally low position, in other words, the diaphragmatic portion of the left ventricle (10 msec); (2) the early arrival of the wave front at the epicardial surface of the diaphragmatic portion of the left ventricle (34 msec); and (3) the subsequent position of the major wave front in the anterosuperior portion of the ventricle with the absence of inferior wave fronts (43 msec). The detailed relationships between the predicted wave fronts shown above and the associated body surface potential distributions depicted in figure 5, I, are presented in the text.
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RICHARD B. KARSH, MADISON S. SPACH and ROGER C. BARR

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