THE ISOPOTENTIAL BODY SURFACE ATRIAL MAPS IN HEALTHY CHILDREN OF DIFFERENT AGE GROUPS

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Isopotential body surface maps during atrial excitation were examined by ten beats addition method of the P waves in 32 healthy children divided into three age groups. The moving pattern of the maxima and the minima, and the distribution of areas of positive and negative potentials in each group were similar to those of adults. Quantitative analysis of the duration and amplitude of the anterior and the left maximum, and the shift time from the former to the latter were done. In children the duration and amplitude of the anterior maximum were always larger than those of the left maximum in contrast to findings in adults where no significant difference was found in their values. The higher amplitude of the anterior maximum was found mainly in the youngest group. These parameters of the P maps were also examined in 12 cases of atrial septal defect (ASD). The amplitude and duration of the anterior maximum were larger than those of healthy children at each age group, although the P wave by the conventional ECG did not reveal signs of right atrial overload. These results suggest that the body surface maps of the P waves are useful diagnostic methods to detect atrial disorders in children.

It has been widely accepted that the body surface isopotential mapping is a useful method for providing information on electrocardiographic diagnosis. This method has also been applied to pediatric cardiology. However, most of the reports deal with the QRS complex and ST-T waves, and only a few reports describe maps with small potentials such as the P wave.

Children's hearts tend to show a predominance of the right side relative to the left when compared to adults' hearts, and the degree of this predominance generally changes with each developmental stage. This is also reflected in the electrocardiographic wave forms so that the P waves in children vary with age. However, the normal ranges of the P wave amplitude and its electric axis as judged by the conventional electrocardiography in children are almost identical to those of adults except for the P time.

We previously reported the body surface maps of the P waves in normal and diseased human adults. This study disclosed that measurements of the maximum and the minimum, and their movements could be obtained in a fairly accurate and reproducible fashion. Therefore, the quantitative analysis of these parameters by the body surface maps of the P wave can be used to diagnose atrial disorders in adults. However, no reports could be made about the P maps in children which show a certain difference from those of adults. We report here the results of the

Key words:
Body surface map
P wave
Atrial septal defect
Children

(Received April 9, 1986; accepted February 12, 1987)
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analysis of body surface maps of the P wave in healthy children who were divided into three age groups.

**MATERIALS AND METHODS**

Thirty-two healthy children aged from two to 13 years (mean 7.8 years) were studied. All had healthy clinical manifestations regarding history, physical findings, chest roentgenogram and standard 12-leads electrocardiogram. The children were divided into three age groups. Group (1) consisted of 10 children from two to five years (mean 3.1 years). Group (2) had nine children from six to nine years (mean 6.6 years). Thirteen children from 12 to 13 years (mean 12.5 years) were included in Group (3). Twelve children with atrial septal defect (ASD) were also examined. Their ages ranged from two to 13 years old. The diagnosis of ASD in all 12 cases was confirmed by cardiac catheterization. The Qp/Qs ratio of the 12 cases ranged from 1.6 to 4.0 (mean 2.5).

A total of eighty-seven electrodes were placed on the children's chest for recording the electric signals, 57 on the anterior chest and 28 on the posterior chest. The sampled area covered the thoracic surface from the level of the clavicle through to the inferior margin of the thoracic cage. Additional electrodes were placed on the extremities to record standard bipolar and unipolar limb leads as well as to drive the Wilson's central terminal. The 87 unipolar electrograms from the body surface and those of six standard limb leads of ECGs were simultaneously recorded during the atrial activations. The method of electrode placement and recording techniques were similar to those reported by Yamada. A body surface mapper (HPM 6500, Fukuda-Denshi Co., Tokyo) was used in this study. The recorded signals were stored in the computer system of the mapper for later analysis and display. The electric signals were sampled at every two or four msec interval throughout the P wave.

Atrial activation maps were obtained by the ten-beat-addition method of the P waves recorded simultaneously. At first we evaluated the accuracy of the P maps obtained by the ten-beat-addition method in 15 normal adults as in the preliminary experiments. The study disclosed that the ten-beat-addition method could give a better recognition of the initial timing and the potential distributions of the P maps than our previous single-beat analysis. The former method could reproduce almost the same pattern as the one obtained by the single-beat analysis; in addition, it could be drawn on the maps automatically because of the larger amplitude in the additioned P waves than the single beat method. The reason for choosing ten-beat in the additioned method was to cover a longer period than one cycle of the respiratory movement. The total amplitudes of electric signals from each recorded point were drawn by the automatic display system of the mapper. The moving pattern of the potential maximum and the minimum were analyzed. Further, three parameters that were proposed by Kawano et al. were examined. They are (A) the duration of the anterior maximum, (B) the duration of the left maximum and (C) the shift time from the anterior maximum to the left maximum after the start of the P wave in lead II. The duration of the anterior maximum indicates the period when the maximum locates at the anterior chest to the right side of the left midclavicular line, and the duration of the left maximum indicates the period during which the maximum is present at the left side of the left midclavicular line. The shift time from the anterior maximum to the left maximum means the period from the start of the P wave in lead II to the time when the maximum migrates to the left across the left midclavicular line. The maximal amplitude of two maxima and of minima were also examined.

The onset of the P wave was determined by three cardiologists in lead II.

Data were analyzed by Student's t-test.

**RESULTS**

The atrial body surface maps were successfully drawn and recorded automatically in all 44 children.

*The moving pattern of the activating atrial maps*

1) Healthy children: A maximum first appeared near the upper part of the sternum on the anterior chest, 0–16 msec after the start of the P waves in lead II. The maximum slowly moved to the middle or lower part of the sternum and stayed there for a while with increasing amplitude. The maximum then migrated to the left side of the chest across the left midclavicular line around the time when the P wave reached its peak. Once the maximum shifted to the left of the midclavicular line, it never moved back to the anterior chest but stayed to the left side of the
posterior thorax until the end of the P wave. A minimum initially appeared on the right shoulder or the right upper back. The minimum gradually shifted to the upper or lower anterior chest, and it stayed at the anterior chest until the end of the P wave without migrating to the left across the midclavicular line.

The area of positive potentials first occupied almost the entire anterior chest except the right upper region and the left lower portion of the posterior chest. The positive area gradually shifted to occupy the left anterior and posterior chest around the time when the P wave reached its peak. It stayed almost at the same place thereafter decreasing the amplitude and the area.

The minus area initially occupied a narrow area of the right lateral chest wall. The area then shifted to the anterior chest and expanded its size until the end of the P wave (Fig. 1, Fig. 2).

The moving patterns of maxima, minima and positive and negative potentials in healthy children were similar for each of the three groups as well as for adults.

2) Children with ASD: The moving pattern of the maximum and the minimum, and the distributions of the area of positive and negative potentials of children with ASD revealed almost the same pattern as those of healthy children (Fig. 3).

The quantitative analysis of the atrial maps

1) Healthy children: In the group (1), (A) the duration of the anterior maximum was 40 ± 6 msec (mean ± SD), (B) the duration of the left maximum was 28 ± 9 msec and (C) the shift time from the anterior to the left maximum after the start of the P waves was 46 ± 7 msec. There was a significant difference between the duration of the anterior maximum and that of the left maximum (p < 0.005). The maximal amplitude of the anterior maximum was 121 ± 18 μV which was higher than that of the left maximum of 102 ± 30 μV (p < 0.025).

(A), (B) and (C) in the group (2) were 40 ± 4 msec, 28 ± 8 msec and 48 ± 5 msec, respectively. A significant difference was recognized in the duration between the anterior and the left maximum (p < 0.005). The maximal amplitude of the anterior maximum and that of left maximum was 115 ± 35 μV and 81 ± 20 μV, respectively. A significant difference was evident in the maximal amplitude between the anterior and the left maximum, as well (p < 0.005).

In group (3), (A), (B) and (C) were 40 ± 5 msec, 31 ± 6 msec and 50 ± 6 msec, in that order. The duration of the anterior maximum was longer than that of the left maximum (p < 0.01). The maximal amplitude of the anterior maximum was 114 ± 24 μV and was higher than that of the left maximum of 91 ± 30 μV (p < 0.05).

There was no significant difference between the groups on the duration of the anterior and left maximum, the shift time from the anterior maximum to the left maximum after the onset of the P wave, the maximal amplitude of the anterior maximum, and that of the left maximum and minimum.

The duration of the anterior maximum was longer than that of the left maximum and the maximal amplitude of the anterior maximum was higher than that of the left maximum in all three groups. The higher amplitude of the anterior maximum was recognized mainly in the youngest group.

The P wave duration obtained by this summing method in group (1), (2) and (3) were 77 ± 12 msec, 82 ± 7 msec and 89 ± 6 msec, in that order.

A summary of these data is shown in Table I and Table II.

2) Children with ASD: In the three cases
TABLE I  MEASURED VALUES OF EACH DURATION IN THREE GROUPS

<table>
<thead>
<tr>
<th>Group</th>
<th>Anterior maximum</th>
<th>Left maximum</th>
<th>Shifting time of anterior maximum</th>
<th>P time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40 ± 6</td>
<td>28 ± 9</td>
<td>46 ± 7</td>
<td>77 ± 12</td>
</tr>
<tr>
<td>2</td>
<td>40 ± 4</td>
<td>28 ± 8</td>
<td>48 ± 5</td>
<td>82 ± 7</td>
</tr>
<tr>
<td>3</td>
<td>40 ± 5</td>
<td>31 ± 6</td>
<td>50 ± 6</td>
<td>89 ± 6</td>
</tr>
</tbody>
</table>

mean ± SD, msec.
*p < 0.01, **p < 0.005

TABLE II  MEASURED VALUES OF EACH MAXIMAL AMPLITUDE IN THREE GROUPS

<table>
<thead>
<tr>
<th>Group</th>
<th>Anterior maximum</th>
<th>Left maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>121 ± 18</td>
<td>102 ± 30</td>
<td>-123 ± 54</td>
</tr>
<tr>
<td>2</td>
<td>115 ± 35</td>
<td>81 ± 20</td>
<td>-91 ± 29</td>
</tr>
<tr>
<td>3</td>
<td>114 ± 24</td>
<td>91 ± 30</td>
<td>-103 ± 39</td>
</tr>
</tbody>
</table>

mean ± SD, μV.
*p < 0.05, **p < 0.025, ***p < 0.005

TABLE III  MEASURED VALUES OF THE DURATION AND THE MAXIMAL AMPLITUDE OF THE ANTERIOR MAXIMUM IN HEALTHY CHILDREN AND ATRIAL SEPTAL DEFECT (ASD)

<table>
<thead>
<tr>
<th>Age</th>
<th>Duration (msec)</th>
<th>Amplitude (μV)</th>
<th>Duration (msec)</th>
<th>Amplitude (μV)</th>
<th>Duration (msec)</th>
<th>Amplitude (μV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy children mean ± SD</td>
<td>40 ± 6</td>
<td>121 ± 18</td>
<td>40 ± 4</td>
<td>115 ± 35</td>
<td>40 ± 5</td>
<td>114 ± 24</td>
</tr>
<tr>
<td>ASD</td>
<td>52</td>
<td>272</td>
<td>52</td>
<td>170</td>
<td>48</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>320</td>
<td>52</td>
<td>175</td>
<td>48</td>
<td>145</td>
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<td></td>
<td>56</td>
<td>154</td>
<td>56</td>
<td>333</td>
<td>72</td>
<td>90</td>
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<td></td>
<td>80</td>
<td>235</td>
<td>84</td>
<td>255</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>416</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The values in ASD indicate the actual data of individual cases at corresponding age groups. The mean values of ASD at each group were not collected, since the numbers of the patients were small.

whose age corresponded to that of group (1), (A), (B) and (C) ranged from 52 to 56 msec, 12 to 32 msec and 64 to 80 msec, respectively, and the maximal amplitude of the anterior and the left maximum varied from 154 to 320 μV and 48 to 122 μV, respectively.

(A), (B) and (C) of the five cases whose age corresponding to that of group (2) ranged from 52 to 80 msec, 12 to 32 msec and 52 to 96 msec in that order, and the maximal amplitude of the
P Maps in Healthy Children

anterior and the left maximum varied from 170 to 416 $\mu$V and 40 to 119 $\mu$V, respectively.

In the four cases whose age corresponded to that of group (3), (A), (B) and (C) ranged from 48 to 84 msec, 12 to 48 msec and 52 to 96 msec in that order, and the maximal amplitude of the anterior and the left maximum varied from 90 to 255 $\mu$V and 84 to 138 $\mu$V, respectively.

The data on the duration and the maximal amplitude of the anterior maximum of these 12 cases with ASD are shown in Table III.

DISCUSSION

Although there are three studies on the human body surface maps of atrial activation sequences, these studies dealt with the P maps of adults and did not examine those of children. In this study, we analyzed the atrial maps of healthy children in three different age groups. The results showed that there was a clear existence of a single maximum and a single minimum, and the distribution of positive and negative areas showed almost the same pattern as those of adults. However, the quantitative analysis of the duration of the maximum and minimum, and their amplitude demonstrate certain differences between the values in children and in adults. Namely, the duration of the anterior maximum was longer than that of the left maximum in all three groups of children. Furthermore, the amplitude of the anterior maximum was always higher than that of the left maximum.

Some problems have been noted for the accurate recording and analysis of the atrial maps because the P wave is such a small amplitude deflection which could easily be influenced by respiratory or body movements. To solve these problems, three reports mentioned above employed different recording methods. In the present study, we used the ten beats addition of the P wave method, which was recently introduced by Kawano et al. This was different from the methods used in the three previous studies. The current method was used because the noise level and the deflection of the isopotential line in children are largely influenced by the respiratory or the body movements especially in younger children so that it is difficult to obtain an accurate P map from the single-beat analysis in children. The time courses of moving pattern of the maxima and the minima were shown to be little affected by the deep respiration in adults. Therefore, it was thought that there was no fundamental problem for adding the P waves, although comparison of P maps between expiratory and inspiratory phase could not be performed in children. By summing ten beats of the P wave, the noise level and variation of the isopotential line are minimized and the constant atrial maps without influences by respiratory or body movements can be obtained. However, this method is not applicable for the analysis of arrhythmias. The accuracy of the atrial maps obtained by this method can be verified by a similarity in P wave values derived from this method and from conventional ECG.

Our observation that there were one maximum and one minimum throughout the P wave in children did not agree with the results reported by Spach et al. and King et al. who showed double maxima reflecting simultaneous right and left atrial activation in experiments with the dog, but they were similar to results from human adult studies.

There were attempts to separate each component produced by the right and the left atrial activation. The P wave was shown to have three peaks by high speed magnified electrocardiogram of the standard 12 leads. The first and the last peak of the P wave obtained by this recording procedure were thought to reflect the activation of the right and the left atrium, respectively. However, one could not tell how much and which atrial activation contributed to produce the middle portion of the P wave. Using the high gain recording of the Frank scalar vectorcardiogram, Ferrer et al. stated that the time from the onset of the P wave to the point of the maximum inferior forces in lead Y and the horizontal crossing time X in lead Z corresponded to the end of the right atrial activation. However, the relevance of these timings to the actual atrial activation was not examined in their study. Furthermore, it can be pointed out that the X axis of the Frank lead system does not necessarily go through the midpoint dividing the right and the left atrium. In addition, their results showed that the time of the shift between the anterior and posterior forces divided by the total P duration had a tendency to increase, and the leftward and posterior forces to decrease with age. These points do not agree with the fact that the right predominance relative to the left side of the heart decreases with age. Therefore, there seems to be no accurate method to distinguish each component of the right and the left atrial activity so far.

*Japanese Circulation Journal Vol. 51, May 1987*
Using the body surface P maps, Kawano et al.7 classified the maximum into two groups by its location, and named them the anterior and the left maximum. The anterior maximum refers to when the maximum locates at the anterior chest of the right of the left midclavicular line, while the left maximum refers to the left of that line. By investigating various diseased conditions, they concluded that the duration of the anterior and the left maximum is the period of predominance of the right and the left atrial activation, respectively. The shift time from the anterior maximum to the left maximum reflects the time when the main activation moves from the right to the left atrium. This analysis was applied to healthy children in this study. We could clearly detect the anterior and the left maximum so that quantitative analysis could be performed. The duration of the anterior maximum were always longer than those of the left maximum in all three groups of children. These findings differed from the adult results which reveal equal durations between the two. The maximal amplitudes of the anterior maximum were also higher than those of the left maximum in all three groups. These differences were smaller in the oldest group than in the youngest one, although the differences were not significant. This finding probably reflects the fact that the right atrium locates close to the chest wall which is usually thin, and the right heart is predominant over the left in children.

A prolonged duration and higher maximal amplitude of the anterior maximum in younger children appear to be of importance in diagnosing right atrial overload. The diagnostic criteria of the right atrial hypertrophy on the conventional ECG and VCG14 in children are the same as those for adults, and did not take into consideration the developmental process and the difference in age. As we showed in this report, as larger numbers of cases are collected, the normal ranges in the P wave maps in each age group will be established by the additional accumulation of data. Consequently, early detection and quantitative diagnosis of right atrial hypertrophy will be available using such a criterion. A small number of children with atrial septal defect were analyzed in this study. Abnormal values above those of each age group of healthy children were detected on the atrial maps even in cases showing no signs of atrial hypertrophy on the standard 12 leads ECG. Therefore, our study concludes that the body surface maps of the P wave can provide accurate diagnostic information for atrial disorders in children.

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