Evolution of QRS and ST-T-wave Body Surface Potential Distributions During the First Year of Life

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SUMMARY Using a system for obtaining body surface potential distributions from 150 sites on the anterior and posterior torso, 43 body surface maps were evaluated in 31 normal infants, ages 15 hours to 10 months. Serial maps were obtained at 0.6-msec intervals during QRS and at 2.4–4-msec intervals throughout the ST-T wave. We found an orderly evolution of both QRS and ST-T-wave maps during the first year of life. In the newborn, the patterns during the latter half of QRS were consistent with early completion of depolarization of the left ventricle and prolonged depolarization of the right ventricle. The patterns changed gradually such that by 5–6 months of age, the maps demonstrated simultaneous effects of both right and left ventricles during the latter half of QRS. By 9 months, the QRS patterns were similar to those of older children and adults. The changes in the ST-T-wave maps were consistent with the idea that age-related changes in the sequence of ventricular repolarization are greatly influenced by the associated age-related changes in the sequence of ventricular activation.

IN NORMAL INFANTS, the QRS and the T wave change rapidly during the first weeks of life, and thereafter they gradually evolve to the adult pattern over many years. However, only minimal information is available, either from direct heart measurements or from total body surface potential distributions, for direct biophysical interpretation or inverse calculation of cardiac electrical events. Thus, the experimental basis is limited for interpreting actual cardiac electrical events from the QRS and T-wave changes that have been documented in previous studies of age-related changes of the 12-lead ECG and of the vectorcardiogram (VCG).

In normal infants, direct heart measurements are not possible. The next best way to study total cardiac electrical activity is to measure the total body surface potential distribution. Total body surface maps provide a means of characterizing the effects of currents from all areas of the heart during both ventricular activation and repolarization. By having the total body surface potential distribution, one can directly predict selective intracardiac electrical events. The total body surface maps also provide a means of determining the extent to which 12-lead ECGs, VCGs and regional precordial maps record the information on the body surface. For example, knowledge of the total body surface potential distribution can alter the ECG or VCG interpretation of cardiac electrical events in right ventricular hypertrophy.

In this paper, we emphasize the qualitative analysis of QRS and ST-T-wave body surface potential distributions in normal infants. We attempt to characterize the movement of the body surface maxima and minima, as done by Taccardi et al. in adults, and to provide preliminary interpretations of the overall body surface potential distributions based on the previous experimental measurements of the relationship between the epicardial and body surface potential distributions in intact chimpanzees by Spach et al.

The purpose of this paper is to provide initial documentation of the total body surface electrical activity as a basis for improving the ability to interpret selective cardiac electrical events from body surface potentials.

Methods

Parental informed consent was obtained for each infant. For infants studied in the first 3 days of life, the consent was obtained prenatally. Generally, the parents accompanied the infant during the recording procedure.

We recorded 43 body surface maps from 31 normal infants, ages 15 hours to 10 months; multiple serial maps were recorded from seven infants. Twenty maps were obtained during the first month (four during the first day and 10 during the first week), 11 during the second month, and 12 during 3–10 months. There were 16 females and 15 males, and 23 Caucasians and eight Negroes. The infants remained healthy and had normal physical examinations at regular check-ups throughout the first year of life.

The maps were recorded with the subjects in the supine position without sedation. To ensure high-quality recordings, the mapping was scheduled to occur with the normal nap time of the infant. The room was lit dimly. The infants were handled gently during the lead placement. Most infants slept during the procedure.

The methods for recording the wave forms and constructing the maps have been described. The vertical electrode spacing was 1.0 cm for small infants and 1.8 cm for large infants. The application of the 150 electrodes is shown for an 18-hour-old infant in figure 1. Vertically oriented straps with 10 electrodes each were positioned to cover the entire thorax and upper abdomen, including the shoulder regions, using 15 straps. Double-adhesive tape was used to hold the straps against the skin. Electrode placement took about 5 minutes, and after the electrodes were in

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FIGURE 1. Recording procedure in an 18-hour-old infant. (left) The rubber straps with electrodes have been pressed to the skin with double-adhesive tape. (right) The infant is swathed in an elastic bandage.

place, the infant was swathed with a wide elastic bandage.

The wave forms were recorded at the 150 positions in subsets of 20 wave forms, along with a time-reference wave form. Thus, the maps were constructed from wave forms during different cardiac cycles. Monitoring the amplitude and shape of the QRS-T complex of the time-reference wave form provided a sensitive means to ensure the similarity of cardiac cycles with respect to the same heart rate and the same phase of respiration in choosing wave forms for construction of the maps. All wave forms were recorded at a sampling rate of 1667 samples/sec, which has been shown to be an adequate minimum sampling rate for QRS wave forms in infants. Data were recorded on digital tape. The entire set of 150 wave forms were recorded within 15-20 minutes.

After the wave forms were recorded, they were redisplayed and photographed for detailed editing to construct the 150-point maps. Baseline adjustment was performed by linear interpolation. Wave forms with irregular baseline movement were discarded from the analysis. Because some infants did not have a clearly demonstrable isoelectric interval between the end of the T wave and onset of the P wave, the PR segment was arbitrarily chosen as the zero baseline potential for construction of the maps. The maps were constructed with automatically drawn isopotential contour lines. Each map during QRS (one for each 0.6-msec interval) and every fourth to ninth map (each 2.4-4-msec interval) during the ST-T wave was photographed for subsequent instant-by-instant and motion analysis. Finally, the standard 12-lead ECG was derived from the final maps.

Results

There was an orderly progression of the changes in both the QRS and the ST-T-wave body surface potential distributions during the first year of life. The format of each map is the same (fig. 2). The torso is represented as a rolled-out cylinder that has been cut along the right axillary line. The resulting rectangle has 16 columns and 10 rows. The far right column has been duplicated by the far left column. The clavicles

maxima and minima are denoted by the large plus and minus signs; their magnitude (in millivolts) is noted above each map. The isopotential lines are drawn on a logarithmic scale; dashed lines indicate negative potentials and solid lines indicate positive potentials. The zero potential line is the prominent dashed line. The representative sequence of QRS maps was obtained during the first day of life (15 hours old). Note the presence of a single excitation maximum throughout QRS.
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and shoulders, as well as the waist and navel, are represented schematically. The isopotential lines are drawn according to logarithmic differences in the voltage values on the body surface. The solid lines represent positive potentials and the dashed lines represent negative potentials. The zero reference potential is indicated by the prominent dashed line. The numbers at each point on the map represent the voltage value at that point (microvolts × 10). These numbers are usually difficult to read in the final published maps. The time instant from the onset of QRS is noted below each map. The vertical mark superimposed on the wave form below each map indicates the relative time instant of that map. During late QRS, there can be a problem in distinguishing maxima and minima that are due to terminal excitation from those of early repolarization. We distinguish between the two based on experimental studies in intact chimpanzees and on the previous interpretation of terminal QRS maps in adults.¹⁶ ¹⁷

Instantaneous QRS Maps of Representative Infants

One-day-old Infant (fig. 2)

In the 1-day-old infant, the initial maximum appeared along the lower left sternal border and the associated minimum was on the back (8 msec). As the maximum increased (20 msec), the area of positive potentials expanded to cover the entire lower torso, and the minimum shifted to the upper back. At 25 msec, an area of negative potentials appeared beneath the left clavicle, a feature that was characteristic of infants during the first month of life (in contrast to adults and older children, in whom the initial negativity on the back extends anteriorly on the right upper chest). By 29 msec, the minimum had moved inferiorly on the left precordium in association with expansion of the negative potential area downward on the left anterior torso. During this interval, the associated positive potentials persisted on the right anterior chest. Thereafter (35 msec), the maximum shifted to the right shoulder and the minimum remained stationary along the sternum; simultaneously, the negative potentials expanded to cover the inferior torso (35 msec). At 43 msec, the terminal positive depolarization potentials decreased in magnitude and disappeared.

One-month-old Infant (fig. 3)

In the 1-month-old infant, during early QRS (7 msec), the maximum was located at the lower left sternal border and the minimum was on the back. Thereafter, the positive potentials extended rapidly to cover the entire lower torso (20 msec) and the minimum shifted superiorly on the back as negative potentials projected anteriorly just beneath the left clavicle. The negative potentials then extended downward to cover the left precordium as the minimum shifted anteriorly just beneath the left clavicle (25 msec). With these changes, the positive-potential patterns also became more complex. The anterior maximum divided into two, one moving inferiorly to a position on the left lateral torso and the other moving to the right on the anterior upper abdomen (27 msec). The left-lower-torso maximum was transient, while the right one persisted (32 msec) and shifted upward to the right clavicle. As the excitation maximum and minimum decreased in magnitude during terminal QRS (45 msec), a new maximum and associated positive potentials developed on the left side of the torso (45 msec). We interpreted these new positive potentials to be the initial manifestation of repolarization on the body surface. (Previous experimental and theoretical analysis has shown that the first extracellular potential change during ventricular repolarization is the development of positive potentials which persist on into the ST segment.⁸ ¹⁸)

Five-month-old Infant (fig. 4)

Early QRS patterns in the 5-month-old infant were similar to those of the younger infants, except that the initial minimum was sometimes located anteriorly on the left chest rather than on the back (the more common location) (fig. 4) (10 msec). By 21 msec, the positive potentials had expanded to cover most of the anterior torso and lower back. The appearance of the anterior chest minimum (30 and 34 msec) occurred on the right upper chest, as in older children and adults, rather than beneath the left clavicle, as in the younger infants. Subsequently, the minimum on the right chest shifted to the left precordium (41 msec). This shift was associated with the division of the single precordial maximum into two maxima; one moved leftward to the back and the other moved rightward to the upper abdomen (41 msec). The left-sided maximum on the back was more prominent and persisted longer than did the similar transient left-sided maximum in the younger infants (fig. 3). However, as QRS continued, the left-sided maximum disappeared and the prominent right anterior maximum shifted superiorly (55 msec) and persisted at the right clavicle until the end of QRS.

Nine-month-old Infant (fig. 5)

Early QRS patterns in the 9-month-old infant were similar to those of the younger infants, i.e., there was an anterior maximum and posterior minimum (11 msec). By 20 msec, the minimum and negative potentials on the back had shifted to the right shoulder region. Then, a new minimum developed rapidly on the upper anterior chest beneath the left clavicle at 30 msec. As the negative potentials and minimum shifted downward on the left precordium, two maxima again emerged from the single left precordial maximum (34 msec). However, in contrast to the events in the 1-month and 5-month-old infants, the right anterior maximum shifted inferiorly and disappeared while the left posterior maximum persisted over the central part of the back. Furthermore, another maximum appeared at the top of the sternum (41 msec). At the end of QRS (51 msec), as the positive potentials of excitation disappeared, a new maximum appeared beneath the left clavicle. Again, we interpreted this new max-
FIGURE 3. QRS maps of a 1-month-old infant. Two excitation maxima transiently appear during depolarization; the maximum at 45 msec was interpreted to be due to repolarization.
FIGURE 4. QRS maps of a 5-month-old infant. Note the development of two prominent excitation maxima, one right anterior and another left posterior.
**Figure 5.** QRS maps of a 9-month-old infant. The maximum at 51 msec was interpreted to be due to repolarization.
imum to manifest early repolarization as demonstrated by the variable patterns of terminal QRS that occur in normal adults.15, 16

**Instantaneous ST-T-wave Maps of Representative Infants**

The sequential changes in the repolarization patterns followed an orderly progression as a function of age. The major change occurred in the distribution of low-level potentials rather than in the position of the maximum and minimum. To illustrate the major features of the evolution of the ST-T-wave patterns from the first day of life to 9 months, we show the potential distributions during the early, middle and late phases of repolarization for three representative infants (fig. 6).

The typical pattern of the ST-T segment (early repolarization) during the first day of life (fig. 6) was that of positive potentials on the left side of the torso and negative potentials on the right side. During the upstroke of the T wave (176 msec), the overall pattern changed little, but the positive potentials became more prominent on the left precordium. Before the peak of the T wave, the positive potential area began to shift from left to right across the anterior chest until most of the anterior chest was covered by positive potentials (262 msec), a pattern that persisted during the latter one-third of the ST-T wave. The wave forms recorded along the right side of the sternum (e.g., the position of lead V4) demonstrated a slightly negative ST segment followed by a positive T wave. The positive T wave coincided with movement of positive potentials across the right side of the chest. In some newborns, this shift was associated with a similar shift of negative potentials on the back; i.e., the negative potentials extended into the left axilla (a region where lead V5 recorded a negative T wave).

In the 1-month-old infant (fig. 6, middle), the ST-segment pattern (83 msec) was similar to that of the newborn. However, during the upstroke of the T wave, the positive potentials did not move to the right side of the chest. The overall pattern remained stable, with positive potentials on the left side of the torso and negative potentials on the right side. However, the magnitude of the positive and negative potentials increased and a prominent gradient developed between the maxima and minima on the anterior chest (205 msec). In contrast to the 1-day-old, the negative potentials were quite prominent over the sternum and adjacent anterior right chest, resulting in deeply negative T waves in that region. Only during the terminal part of the T wave did positive potentials migrate across the sternum to the medial portion of the right side of the chest (250 msec).

After 1 month of age, the pattern of the ST-T wave showed little change (fig. 6, bottom). Again, during the ST segment there were positive potentials on the left side of the torso and negative potentials on the right side (83 msec). The primary change during the upstroke of the T wave (220 msec) was the increase in the absolute values of the positive and negative potentials, rather than a change in the pattern. That is, during the peak and downstroke of the T wave, positive potentials did not migrate across the anterior chest as in the infants during the first month of life.

The repolarization patterns remained relatively constant after 1 month of age, and the patterns were similar to those of normal adults.18 However, in contrast to the low-level negative potentials that occur on the right anterior chest during the T wave in normal adults, these infants had markedly negative potentials on the right anterior chest and sternum with a prominent gradient in the region of the sternum. These distributions are consistent with the fact that young children have clearly negative T waves in lead V5.

The QRS and ST-T-wave map patterns were quite age-specific; changes strictly related to sex or race were not obvious. Serial map recordings in the same infant confirmed the general trends that occurred with changes in age. The map patterns for both QRS and ST-T waves were homogeneous for young infants in the first few days of life as well as in older infants. The greatest variations were in infants with intermediate ages. For example, variation was seen in the age at which the single right-sided maximum evolved into two maxima. However, we could usually estimate the infants’ age (e.g., young, intermediate, or older infant under 1 year), after viewing their QRS and ST-T body surface maps.

**Discussion**

Two major points are established in this study. First, the changes in depolarization of the ventricles during the first year of life produce an orderly progression of change in the total body surface potential distributions during the QRS complex. At birth, a single early QRS maximum moved to the right during the latter half of QRS; at several months of age, the initial maximum evolved into two maxima (one moving to the right and the other to the left); finally, the initial maximum moved to the left side of the thorax while the right-sided one almost disappeared. Second, there was an association between the age-related changes in the QRS maps and the repolarization maps: at birth, the QRS and the ST-T-wave positive potentials shifted to the right anterior chest during the latter part of ventricular excitation and during the latter half of repolarization. With increasing age, movement of both the excitation and the repolarization positive potentials to the right chest did not occur.

These features suggest a relationship between the body surface events and those in the right and left ventricles. In the absence of direct cardiac measurements to establish an electrical model of the ventricular events after birth, the maps may provide a basis for some qualitative conclusions (realizing that the real electrical events in the ventricles are considerably more complex than can be interpreted from body surface maps).

The age-related changes in the movement of the QRS maxima and minima are summarized in figure 7. The most obvious change is that at birth, the initial QRS maximum moves from the central anterior chest to the right side of the thorax, whereas at 9 months the initial QRS maximum moves from the central
FIGURE 6. Representative ST-T-wave maps of a 1-day-old infant, a 1-month-old infant, and a 9-month-old infant. The positive potentials are represented by the darkened area.

FIGURE 7. Movement of QRS maxima and minima during the first year of life. The plus and minus signs denote the position of the maximum and minimum at the onset of QRS. The arrowheads show the position of the maxima and minima at the end of QRS. The width of the arrow (narrow, broad) indicates the relative time of duration of the indicated maximum or minimum; that is, broad arrows indicate extrema that persist for most of QRS and narrow arrows indicate those that are transient.
anterior chest to the left axilla. Only one general interpretation is possible for this marked difference in the movement of the QRS maximum in normal infants: At birth, the movement of the QRS maximum during the latter half of QRS is determined primarily by currents from the right ventricle and at 9 months of age by currents from the left ventricle. This is in agreement with the long-standing interpretation of age-related QRS changes in the standard ECG and the VCG after birth. However, while the well-known normal transitional change in the right ventricular peak systolic pressure from a systemic level to a low peak-systolic pressure occurs within a few hours to a few weeks, the transition of the QRS map patterns from marked right ventricular predominance at birth to the predominant left ventricular pattern lags behind the hemodynamic change for a considerable time. The first identifiable effects of the currents from the left ventricle appeared around 1 month of age; i.e., while the rightward-moving maximum occurred during the latter part of QRS (presumably due to currents from the right ventricle), a separate and transient maximum developed simultaneously and moved toward the left axilla (fig. 7). It is reasonable to assume that the transient leftward moving maximum was produced by wave fronts in the left ventricle. This assumption appears justified on the basis that this pattern continued to increase with age so that by 5 months the two maxima became equally prominent, one moving over the right chest and the other toward the left axilla (fig. 7).

Body surface map patterns sometimes have been associated with specific intracardiac electrical events. For example, epicardial breakthrough in the normal adult heart (which occurs in the anterior wall of the right ventricle) has been documented in chimpanzees and dogs, and the pattern is generally agreed upon for adult humans. Although "epicardial breakthrough" is a specific intracardiac event emphasized in the interpretation of QRS body surface maps, we cannot, on the basis of surface maps alone, make what we consider accurate estimates of this intracardiac event, other than for normal adults and older children. However, the patterns summarized at 1 and 5 months in figure 7 indicate that the two simultaneously present maxima, which are located at such widely divergent positions (with a prominent minimum in between the two) are related to excitation currents generated separately from the right and left ventricles. Not until 5 or 6 months of age did a maximum occur during QRS which could convincingly be related to left ventricular excitation events. These results suggest that although there are many hemodynamic, metabolic and innervation changes of the ventricles that occur during the first 6 weeks of life, change in the overall pattern of ventricular excitation requires a much longer period; i.e., it changes over many months. Even at 9 months (fig. 7), when the typical progression of the maxima and minima was associated with predominantly left ventricular events (well established for adult hearts), a second transient maximum still occurred and shifted onto the right anterior chest during the middle of QRS, a clear reflection on the body surface of persistent right ventricular wave fronts.

The age-related changes in the patterns of repolarization are more difficult to interpret. The prominent differences between the newborn repolarization pattern and that of the older infants suggest a crude electrical model of change consistent with previous experimental and theoretical work. Spach and Barr showed in intact adult dogs with normal hearts that with a normal activation sequence, the predominant repolarization potential gradient determining the epicardial potential distributions was from endocardium to epicardium. In the adult heart with a normal sequence of ventricular activation, the total time for activation of both ventricles is short, and the normal adult repolarization potential gradients are produced primarily by regional differences in the duration of the ventricular action potentials; that is, the normal pattern of intracellular and extracellular current flow throughout the ST-T wave in adult hearts is determined primarily by a potential gradient that is oriented normal to the epicardial surface (transmural gradient). However, when the excitation sequence is altered so that one ventricle completes its excitation while activation continues for a relatively long time in the other ventricle, the effects of propagation across the heart overwhelm those due to the transmural gradient during repolarization. The predominant potential gradient then exists across both ventricles (transventricular gradient) to produce different ST-T-wave epicardial potential distributions compared with those of the normal ventricular activation sequence.

In the newborn, repolarization was initiated with positive potentials on the left side of the torso; as repolarization continued the low-level positive potentials migrated across the anterior chest from left to right. Movement of the positive potential area indicates the order of repolarization, reflecting the propagation of repolarization in the ventricles. That is, the repolarization maximum in the heart shifts from the earliest site of excitation toward the terminal site of excitation. The repolarization patterns of the 1-day-old infant (fig. 6) suggest the appearance of repolarization in the left ventricle and the termination of ventricular repolarization in the right ventricle. This interpretation is consistent with the associated interpretation of the movement of the QRS maxima and minima (early completion of activation in the left ventricle and prolonged activation of the right ventricle). Thereby, an overall left ventricle-to-right ventricle repolarization sequence would account for the well-known upright T wave in lead V1 in normal newborn infants (fig. 8).

The repolarization patterns after 1 month of age were quite similar to those of normal adults, except that the absolute values of the negative potentials on the anterior right chest were clearly greater than those
FIGURE 8. ECGs of a 1-day-old infant, a 1-month-old infant, a 5-month-old infant, and a 9-month-old infant. The tracings were derived for the designated leads from the body surface maps of the representative infants whose potential distributions are shown in the previous figures.

in normal adult body surface maps. Since the repolarization patterns were so similar to those of adults, but quite different from those of the 1-day-old infants, we think that the age-related changes in the repolarization pattern are due in large part to changes in the sequence of repolarization secondary to changes in the sequence of ventricular excitation; as the ventricles become almost simultaneously depolarized with increasing age, the repolarization sequence is altered to appear more like the normal adult pattern. The existence of age-related regional changes in the shapes of ventricular action potentials is unknown. However, it is unlikely that age-related regional changes in the shapes of the action potential alone could account for the major differences in the repolarization maps of the 1-day-old infant and the 9-month-old infant, especially in view of the explanation that marked changes in the ventricular excitation sequence also cause marked changes in the sequence of repolarization.

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