Representation of Cardiac Electrical Activity by a Moving Dipole for Normal and Ectopic Beats in the Intact Dog

PIERRE SAVARD, FERNAND A. ROBERGE, JEAN-BENOIT PERRY, AND RÉGINALD A. NADEAU

SUMMARY We evaluated the ability of a computer procedure to locate cardiac electrical activity from body surface potentials during normal and ectopic beats in six intact dogs. The location of the dipole that best reconstructed the signals recorded from 26 thoracic electrodes was computed by using a torso model. This model was designed from geometrical measurements made on the first dog. Chronically implanted subepicardial electrodes produced ectopic foci at three known locations: apex, and right and left ventricles. For the normal QRS complex, the dipole started in the middle of the septum, moved upward, then to the left, downward, and back to the right; it remained stationary at the level of the base during repolarization. After ectopic stimulation the dipole started its course at a distance of 1.9 ± 0.8 (SD) cm from the stimulus site and then traversed the heart, moving away from the ectopic site; during the T wave, it roughly followed the QRS path, but at a slower speed. The speed of the dipole ranged between 0 and 6 m/sec, and its orientation often did not coincide with the direction of its path. The location of the dipole appeared to be close to the corresponding wavefronts when these were unique and dipolar, especially during the early and terminal portions of the QRS. The results show that the initial location of the dipole can give the approximate position of an ectopic focus in vivo, and that the trajectory of the dipole during QRS can portray the passage of an ectopic beat across the heart.


PREVIOUS work on calculations of cardiac electrical sources from body surface potentials has been based on representing the heart by multiple dipoles (Barnard et al., 1976) or by epicardial potential distributions (Barr and Spach, 1978). Another possible representation is a single moving dipole (SMD). It is a current dipole whose location, amplitude, and orientation are optimally fitted to the measured body surface potentials. The SMD concept was introduced by Gabor and Nelson in 1954 and since has been applied to the study of normal cardiac cycles in human subjects (Arthur et al., 1971; Guardo, 1972; Horan and Flowers, 1971; Kneppo and Titomir, 1979) and in pigs (Hodgkin et al., 1976). During the past few years, the SMD representation has been investigated extensively with a simple in vitro preparation. Isolated rabbit or turtle hearts were suspended in a spherical electrolytic chamber, and the SMD parameters were computed from the chamber surface potentials (Brody et al., 1971). These studies showed that the SMD could accurately locate epicardial burns or subepicardial pacing sites (Ideker et al., 1975). The SMD also could provide information about spontaneous and ectopic cardiac cycles (Ideker et al., 1977), the dipolar behavior of the T wave generator (Brody et al., 1977), bundle branch blocks (Brody et al., 1974), and acute ischemic lesions (Mirvis et al., 1978a).

Although some of the results reported for human subjects are plausible, they cannot be verified fully since the actual trajectory of the SMD is not known. This information was precisely available in the controlled in vitro experiments. Thus, these were able to demonstrate that the computed location of the SMD can be used to locate small dipolar sites of electrical activity and to depict the passage of an ectopic beat across the heart. The present study was designed to bridge the gap between these two approaches with a new in vivo evaluation of the SMD representation. Subepicardial stimulation electrodes were chronically implanted in dogs. They produced electrical foci at known positions which served as references against which the accuracy of the computed SMD location could be judged. Initially, a computer model of the canine torso was constructed from anatomical measurements made on a dog from which the body surface potentials also had been recorded. In subsequent experiments, the SMD parameters were computed for dogs different from the one used to construct the torso model. Accordingly, the procedure tested was one that could be used with any dog, given only a few geometrical reference points and a sufficient num-
ber of body surface potential measurements. Compared to the in vitro experiments that simplified the thoracic volume conductor, this procedure provides a more realistic evaluation of the clinical possibilities of the SMD representation.

Methods

Experimental Measurements

Experiments were carried out on six mongrel dogs, weighing 20–30 kg, anesthetized with sodium Pentothal (30 mg/kg, iv). Ventilation was maintained with a Harvard pump. The heart was exposed through a left thoracotomy at the level of the 5th intercostal space. Bipolar subepicardial stimulation electrodes were implanted on the right ventricle near the pulmonary artery (Fig. 1, site RVB), on the lateral wall of the left ventricle (site LVW), and on the apex (site APEX). Two unipolar detection electrodes also were sutured to the atria. All leads were channelled to a subcutaneous pouch in the neck. A chest tube was connected to a water seal to remove air from the thorax. The chest was closed in layers and the dog allowed to recover.

Studies were performed 8–15 days postoperatively, again under sodium Pentothal anesthesia. The signals from the two atrial detection electrodes triggered a programmable stimulator (Billette et al., 1979) which delivered a 3-msec pulse to one of the three ventricular electrodes at twice the threshold value. The delay between detection and stimulation was adjusted to produce an extrasystole. The heart rate was between 120 and 160 beats/min.

The body surface potentials were recorded with 26 unipolar leads referenced to the Wilson central terminal. All recordings were taken at the end of expiration. The electrodes (Grass E2b) were placed uniformly around the thorax in three rows of eight equidistant electrodes (Fig. 2) (Guardo, 1972, Nelson et al., 1971). The central row was located at the level of the 6th intercostal space, and the other two were placed 7 cm away on each side. Two additional electrodes on the neck and lower abdomen made up the 26 electrode array. The 26 ECG signals were amplified using low input bias current amplifiers with a bandpass of 0.05–200 Hz. Two additional amplifier channels were available for recording auxiliary signals, e.g., a stimulation signal or a conventional ECG. The signals were multiplexed at a sampling rate per lead of 400/sec and converted to digital form with a resolution of 12 bits. The sampling and conversion time was 10μsec/channel, leading to a total conversion time for all 28 channels of less than 30 μsec. This time skew among channels was considered negligible compared to the interval between successive samples of 2.5 msec. Data were recorded on a 9-track digital magnetic tape.

The geometric coordinates of the torso model and electrodes were obtained for the first dog as follows: A reference rod representing the Y axis was supported longitudinally above the sternum, and 12 marks, 3.5 cm apart, were made on it. These marks represented the positions of 12 transverse torso sections. It was arranged for the central row of electrodes to fall between marks 6 and 7. For each of the 12 sections, the coordinates of the canine torso surface in the X-Z plane were recorded by using an electronic pantograph. The left and right sides of these cross sections were rendered symmetrical by computer processing, and 20 uniformly distributed points were chosen along each of their
contours to represent the vertices of the triangles used to construct the torso model. The coordinates of the 26 thoracic electrodes were recorded by the same technique, and each electrode was assigned to the nearest triangle. For subsequent dogs, it was assumed that this model represented the torso sufficiently accurately. Every effort was made, however, to select dogs of similar build and to place the electrodes with a fair amount of consistency.

The diastolic positions of the stimulation electrodes were obtained in all dogs from frontal and sagittal fluoroscopic projections. The maximum error for the fluoroscopic measurements was estimated at ±1 cm. For each dog, the same coordinate system as that of the torso model was used. The origin was a point over the sternum, at the level of the 6th intercostal space. The frontal and left sagittal views of the cardiac silhouette (Fig. 1) were obtained for the first dog from the anatomical and geometrical positions of the electrodes.

Mathematical Methods

The calculation of the location, amplitude, and orientation of the SMD was based on methods developed by Arthur and Geselowitz (1970) and Arthur et al. (1971). These methods rely on the canonical representation of the cardiac sources by a multipole expansion. For biological sources, the first three terms of this expansion are dipole components, and the next five terms are quadrupole components. The subsequent terms of higher order provide a smaller contribution to surface potentials (Mirvis et al., 1978b; Cuffin and Geselowitz, 1977; Arthur et al., 1972) and were neglected in the present study.

The potential due to a multipole source was computed on each of the 480 triangles of the computer model. This model represented the torso as a finite and homogeneous medium (Barnard et al., 1967). The origin of the multipole expansion was placed at the center of the heart, as determined from the fluoroscopic images. The conductivity of the torso was assumed to be 0.2 mho/m (Rush et al., 1963). The transfer matrix A (Equation 1) was obtained from the eight potential distributions due to the first eight multipole sources of unit strength. In this matrix A, element aij relates the surface potential Vj at recording site i, to the multipole component Xj. The transfer matrix A has 26 rows, corresponding to the number of thoracic electrodes, and eight columns corresponding to the multipole components.

\[ v = A x \]  

For a given surface potential distribution, a least squares error fit was used to establish the required magnitude of each of the eight multipole components. This leads to a solution for x given by Equation 2, where superscripts T and \(-1\) refer to transpose and inverse, respectively:

\[ x = (A^T A)^{-1} A^T v. \]  

In the multipole expansion, a shift in the position of the origin, while altering the quadrupole components, does not affect the three dipole terms. This forms the basis of the inverse solution for the location of the SMD. The origin of the multipole expansion is shifted so as to minimize the coefficients of the quadrupole terms (Geselowitz, 1965). The solution is given by:

\[ r_0 = M^{-1} (M^2 I - \frac{1}{3} M M^T) Q M, \]  

where the column vector \( r_0 \) gives the coordinates \( x_0, y_0, z_0 \) of the SMD; the column vector M contains the computed dipole terms of Equation 2; \( M^2 \) is the square of the dipole amplitude; I is a 3 \( \times \) 3 identity matrix; and Q is a 3 \( \times \) 3 matrix representation of the quadrupole terms of Equation 2 (Arthur and Geselowitz, 1970).

Computational Methods

Data processing was done on a PDP-11/40 minicomputer. In the case of spontaneous heartbeats, the operator determined the beginning and end of QRS by moving pointers on the displayed ECG. For
ectopic beats, the ventricular stimulation time was taken as the beginning of QRS. Baseline shift was corrected by selecting two points in the T-P intervals of successive heart cycles and by measuring the ECG signal from the straight line so defined.

Isopotential contour maps of chest potentials were obtained for every sampling instant (2.5 msec) during QRS and at each 10 msec during S-T and T wave. They were presented in a rectangular format corresponding to unrolling the torso after slicing it along the dog's spine (Fig. 1). The upper edge of the rectangle corresponds to a level midway between the neck electrode and the top row of electrodes, and the lower edge to one midway between the abdominal electrode and the bottom row of electrodes. The isopotential lines were obtained by polynomial interpolation. The minimum increment between successive contour levels is 0.075 mV. This increment was increased automatically by the computer for large potential gradients so as to prevent clustering of the contour lines. The zero potential contour is identified by a heavier trace. Plus and minus signs indicate the positions of the maximum and minimum.

The SMD location was computed for every sampling instant during QRS and T wave. However, results were displayed only when the dipole amplitude exceeded 10% of its peak value. Low signal-to-noise ratio values obtained during early and late portions of QRS and T wave gave rise to unrealistic shifts in the dipole origin.

Results

The effects of thoracotomy were assessed by comparing pre-and postoperative normal QRS. For all dogs, pre- and postoperative vector loops were similar. The SMD courses showed more differences, but their general features were retained. In the initial dog, the path of the SMD was essentially the same after thoracotomy, except for an overall shift to the right by about 1 cm.

Normal Beat

The path of the SMD, vector loops, and body surface potential maps are displayed in Figure 3 for the normal activation sequence in the initial dog. At 10 msec after QRS onset, the amplitude of the SMD exceeded 10% of its maximum value, and its location was in the middle of the septal wall, 2 cm below the approximate position of the base of the heart. The dipole was oriented ventrally, slightly to the right, and positive potentials covered all of the ventral surface. During the following 15 msec, the SMD moved 1 cm upward and then 2 cm to the left.

**Figure 3** The course of the SMD, vector loops, and isopotential contour maps for the normal QRS in the initial dog. The following figures are all presented in the same format. In the frontal, left sagittal, and transverse planes, the successive locations of the SMD at 2.5-msec intervals are joined by a dotted line, and arrows show the direction of the path. At each point, the projection of the corresponding normalized dipole vector is shown in the same plane. The numbers alongside the path refer to the time in milliseconds after QRS onset. Some of the points may be superposed when the SMD speed is low. The location of the dipole is not displayed for very early and late portions of the QRS. The three vector loops are the successive projections of the SMD vector tip (but with a fixed origin). The length of the projection axes for the vector loops is 7.5 mm. Isopotential contour maps corresponding to three instants are shown. The increment between successive contour lines as well as the amplitude of the maximum (+) and minimum (−) are indicated under each map. The zero potential contour is identified by a heavier trace. The reference ECG was recorded in left precordial area.
with a maximum speed of 3.5 m/sec. The orientation of the dipole became more caudal and leftward. At 20 msec, the orientation was perpendicular to the path of the dipole.

At 25 msec, the location of the SMD was 1 cm below the base, on the central axis of the left ventricle. Its orientation was ventrocaudal and leftward; the map showed a maximum in the left precordial area along with a minimum on the superior right chest. Afterward, the dipole moved about 1 cm to the left, then 1 cm in the ventral direction and shifted rapidly 3 cm to the right. The orientation of the dipole also changed from ventral to dorsal.

At 40 msec, the SMD reached a point 1 cm to the left of its starting position inside the left ventricle with a maximum speed of 6 m/sec. The dipole was oriented dorsally and slightly to the left; negative potentials covered all of the ventral surface. During the next few instants, the SMD moved 1 cm upward, and its amplitude dropped below 10% of its maximum value, thus interrupting the display.

For the other dogs, the vector loops were similar to those of the initial dog. The SMD courses showed more variability, but their general features were the same: the septal origin, the initial upward movement, the leftward displacement during the middle part of the QRS, and the fast rightward shift at the end of the QRS. The overall displacement of the SMD was larger, especially along the Y axis, but the SMD location stayed within the cardiac silhouette.

RVB Ectopic Stimulus

At 40 msec after stimulation of the right ventricle, the dipole was located 1 cm away from the stimulation electrode (Fig. 4). It then was oriented caudally and slightly to the right; positive potentials covered all of the lower torso and ventral surface, and the minimum was on the left superior chest. The dipole moved 1.5 cm to the right during the next 15 msec, then it moved to the left and caudally with a maximum speed of 2 m/sec. The orientation of the dipole remained caudal.

At 70 msec, the location of the dipole was in the central axis of the left ventricle, just below the base. The orientation was caudal, slightly dorsal, and leftward; the maximum was located in the lower left torso and the minimum in the upper right chest. Afterward, the dipole continued its course in the same direction at the same speed for about 20 msec and then accelerated dorsally and toward the right with a maximum speed of 3.4 m/sec.

At 110 msec, the location of the dipole was in the posterior wall of the left ventricle slightly below the base. The dipole orientation still was caudal and leftward. This coincided with a minimum on the right superior chest and a maximum on the lower left torso.

For the other dogs, the vector loops were oriented more toward the left. The SMD courses retained the same features as for the initial dog: the beginning of the path in the vicinity of the stimulus site, the initial shift to the right, the downward movement toward the left, and finally, the end of the path in the posterolateral wall of the left ventricle.

LVW Ectopic Stimulus

At 45 msec after stimulation of the left ventricular wall, the location of the dipole was 2.5 cm to the right of the stimulation electrode (Fig. 5). During the next 30 msec, the SMD moved 2 cm dorsally at a speed of about 1.6 m/sec while keeping the same rightward orientation which thus was perpen-

**Figure 4.** The SMD course and isopotential maps for RVB ectopic stimulation in the initial dog. The location of the stimulus site is indicated by a filled circle. The length of the projection axes for the vector loops is 10 mm, and the numbers alongside the path refer to the time after stimulation. The same format as in Figure 3 is used.
The SMD course and isopotential maps for LVW ectopic stimulation in the initial dog. The vector loop projection axes are 10 ma-mm long. The same format as in Figure 3 is used.

Figure 5

At 75 msec, the dipole was in the middle of the left ventricle and still oriented to the right. Positive potentials covered the superior and middle right chest. Afterward, the dipole moved 2 cm to the right and then leaped 5 cm upward with a maximum speed of 7 m/sec. The orientation of the dipole was in the same upward direction.

At 100 msec, the dipole was entering the right atrium, near the pulmonary valve. The orientation was upward and well related to the potential distribution on the surface of the chest which showed a maximum over the upper part of the sternum.

In four other dogs for which electrical data were available, the vector loops were similar to those of the initial dog, but oriented slightly more ventrally.

At 45 msec after stimulation of the APEX site in a subsequent dog, the SMD was located 1.1 cm above the stimulation electrode (Fig. 6). During the next 15 msec, the SMD moved 4 cm upward with a speed ranging from 6 to 1.5 m/sec. The orientation of the dipole was upward, parallel to the central axis of the heart, and it remained the same throughout the QRS. Accordingly, positive potentials covered the upper part of the torso, and negative potentials covered the lower part. At 75 msec, the SMD was located at the center of the heart. Between 60 and 80 msec, the MD interrupted its upward course with a 1 cm back and forth shift toward the back. It then resumed its upward course while the orientation of the dipole became more ventral. At 95 msec, the dipole was located inside the right atrium. The orientation of the dipole was upward.

In the other dogs, stimulation of the APEX site produced a very reproducible trajectory which spanned across the entire cardiac silhouette from apex to base. The SMD started its path at an average distance of 2 cm from the stimulation electrode. The SMD moved essentially upward, along the central axis of the heart. Between 60 and 85 msec after stimulation, the SMD moved more slowly and formed a small loop near the center of the heart, then resumed its upward course. The trajectory ended at the base of the heart approximately 105 msec after stimulation. The SMD vector retained the same upward orientation throughout the QRS. Results for subepicardial apical stimulation were not available in the initial dog.

Repolarization Sequences

The repolarization sequences showed marked differences between normal and ectopic beats. For the normal beat (Fig. 7A), the T wave vector had the same orientation as the mean QRS vector. For ectopic beats (sites RVB and LVW, Fig. 7, B and C, respectively), the QRS and T wave vectors were opposite. Also, ectopic T wave vectors were grossly parallel to the line joining the geometrical center of the heart and the stimulation site. The position of
the SMD during the normal T wave remained almost stationary at the level of the base, near the septum. During ectopic T waves, the course of the SMD had a more constant orientation and speed. For site RVB, the overall direction of the path of the dipole was caudal but went up and down during the T wave upstroke. For site LVW, it was simply upward. For both sites, the speed of the dipole was quite low during the first part of repolarization when the dipole was approximately in the center of the left ventricle, but during the second half of the T wave, it accelerated to 0.4 m/sec.

For the other five dogs, the orientations of the T wave vectors were similar to those of the initial dog. The normal beat T wave vector had the same orientation as the mean QRS vector, and the ectopic T wave vector and mean QRS vector were opposite (sites RVB, LVW, and APEX). For the normal heartbeat, the location of the SMD remained stationary at the level of the base, as in the initial dog. The RVB ectopic stimulations in four dogs produced a T wave SMD location which moved from the center of the heart to the left, slowly during the main part of the T wave, then faster at the end; one other dog showed the same downward shift as the initial dog. The LVW ectopic stimulation produced the same upward SMD shift as the initial dog, moving slowly during the main part of the T wave, then faster at the end. For the APEX stimulation, the T wave SMD course was similar to the QRS course: an upward shift along the central axis of the heart, from the apex to the base.

Discussion

The relationship between cardiac electrical events and SMD computations can be understood best by first considering a uniform dipole layer

![Figure 6](image-url) The SMD course and isopotential maps for APEX stimulation in a different dog. The position of the stimulus site was obtained from fluoroscopic projections in the same coordinate system as for the initial dog. Computations were carried out with the torso model of the initial dog and the cardiac outlines in this figure are also those of the initial dog. This explains the position of the stimulation electrode outside the cardiac silhouette. The vector loop projection axes are 10 ma-mm long.

![Figure 7](image-url) Trajectories and vector loops of the SMD during the T wave for the initial dog. Frontal projections for the normal spontaneous heartbeat (panel A), RVB ectopic stimulation (panel B), and LVW ectopic stimulation (panel C).
source representing an activation wavefront. Brody et al. (1962, 1977) have shown that for such a dipole layer source with a planar rim in an homogeneous conducting medium, the magnitude, orientation, and centroid of the rim area determine, respectively, the amplitude, orientation, and location of the equivalent dipole. This layer source also generates higher order multipole components related mainly to size (Mirvis and Larsen, 1979). Multiple wavefronts and wavefronts with nonplanar rims are nondipolar, i.e., they cannot be represented well by a single dipole. This is the basic limitation of the SMD representation.

Initial Location of the Dipole for Ectopic Beats

The position of the SMD at 45 msec after stimulation and the position of the corresponding stimulation electrode are shown in Figure 8 for the three ectopic sites and the six dogs. The initial locations of the SMD are grouped into three distinct clusters corresponding to the three ectopic sites. The mean distance between the electrodes and the SMD locations is 1.9 ± 0.8 (SD) cm.

The initial SMD location after stimulation may not correspond to the position of the electrode because of intrinsic or cardiac factors, such as wavefront displacement and nondipolarity. Because of the noise, the location of the dipole was displayed only when the dipole magnitude exceeded a certain threshold, and this occurred from 15 to 40 msec after the stimulus, at which time the wavefronts may have moved away from the electrode. As for the nondipolarity of these initial wavefronts, Spach and Barr (1975a) have described two parallel wavefronts moving in the lateral wall of the left ventricle for the LVW site and a long wavefront facing both anteriorly and posteriorly in the free wall of the right ventricle for the RVB site. These activation fronts, occurring about 40 msec after the stimulus, are not represented well by a single dipole. For two similar stimulation sites on the isolated rabbit heart, Ideker et al. (1977) have computed the fraction of the root-mean-square (RMS) surface potentials that cannot be accounted for by a single locatable dipole. This "nondipolarity index" showed that the beginning of the right ectopic sequence was nondipolar and that the left one was relatively dipolar.

Ideker et al. (1975) reported a distance of 3.7 mm with a range of 2.6-4.6 mm between the initial SMD location and a subepicardial pacing electrode implanted in the left ventricle for six isolated rabbit hearts. The difference between these results and ours is due mainly to dissimilar experimental preparations. For the in vitro experiments, the same spherical electrolytic chamber was used for all hearts. This chamber eliminated the variations in torso geometry between animals and the effects of thoracic electrical inhomogeneities such as the lungs. It also permitted the use of a different mathematical technique and exact measurement of electrode locations by photographic triangulation. In the present study, the fluoroscopic projections of the electrodes were precise to only 1 cm. Thus, the in vitro experiments eliminated many extraneous or noncardiac factors affecting the accuracy of the SMD evaluation. These factors were present in our dog experiments and also would be present in a clinical situation.

Migration of the Dipole

The speed and moment of the SMD and the SMD trajectory also can provide some information about the cardiac electrical sources during the QRS and T wave. However, the interpretation of the SMD trajectory is complicated because multiple wavefronts are represented by a single equivalent dipole. Some authors have described the SMD as the "moving electrical center" of the heart (Arthur et al., 1971; Kneppo and Titomir, 1979). This expression, suggesting that the SMD is similar to a "center of gravity," is inappropriate since the SMD location generally will not coincide with the center of gravity of multiple dipolar sources. For some source configurations, the SMD even can be located outside the perimeter enclosing the sources (Fig. 9A). The relationship between the SMD location and several distributed sources is not as straightforward as for the SMD amplitude and orientation which are simply the vectorial sum of all the source vectors. The exact location of the SMD representing multiple
The cardiac electrical events which are portrayed during ventricular activation reportedly occurs in the lower ventricular septum with a wavefront facing toward the right. The position of the moving dipole at 10 msec is also in the septum, 2 cm below the base and oriented ventrally and toward the right (Fig. 3). Afterward, as reported by Spach and Barr (1975a), the activation is propagated rapidly in many directions by the specialized conduction system, and at 24 msec, most of the free wall of the right ventricle is depolarized, and the main wavefront is enveloping the left ventricle, facing toward the left. At the same time, the SMD was in the middle of the left ventricle, oriented along the main axis of the heart. During the terminal portion of the QRS, the presence of two wavefronts is reported respectively in the left ventricular free wall and in the posterior basal region. This latter front lasts to the end, facing posteriorly. At 35 msec, the moving dipole was in the left ventricular free wall, facing to the left, but during the next 7.5 msec, it leaped toward the right and posteriorly with a speed of 6 m/sec. This fast shift from one end of the heart to the other is representative of the presence of two distant wavefronts and of the sudden decrease of one of them.

For ectopic beats, the published depolarization wavefronts spread across the ventricles from the stimulating electrode to the opposite side of the heart. This was portrayed in the present study by the course of the SMD. From a site corresponding to the RVB electrode, the excitation wave was reported to propagate first across the anterior right ventricular wall away from the atrioventricular ring, then into the right lateral wall posteriorly. This pattern is depicted in Figure 4 by the initial rightward and dorsal shift of the caudally and rightward-oriented dipole. The wavefront then reaches the septum at 53 msec, having the shape “... of a single flat plane which bisected the heart with negative potentials enveloping the right ventricle and positive potentials enveloping the left” (Spach and Barr, 1975a). This general pattern is represented by the course and moment of the dipole, but it is somewhat early in comparison with the leftward shift of the dipole which began only at 55 msec and the leftward orientation of the dipole which became apparent only after 70 msec. The excitation wave has been shown to end in the posterior wall of the left ventricle, near the atrioventricular ring. At the end of QRS, the SMD also was in the posterior wall of the

### Figure 9
The equivalent dipole for three dipole sources configurations (A, B, C) and for a moving activation wavefront (D). The dipole sources are represented by light arrows and joined by dashed lines in A, B, and C. The equivalent dipole is depicted by a heavy arrow. In panel C, the dotted line indicates the locus of SMD locations for two dipole sources with different amplitude ratios but with fixed location and orientation. In panel D, a wavefront moving in a triangular surface is depicted at equal time intervals by horizontal lines, and the successive SMD locations are joined by a broken line.
left ventricle near the septum and oriented toward the left.

For the site corresponding to the LVW electrode, two distinct wavefronts have been reported in the lateral wall of the left ventricle with quite different orientations at 46 msec. At this time, the path of the SMD in the transverse plane was a small circle 2.5 cm to the right of the stimulus site (Fig. 5). This erratic behavior may be attributed to the nondipolar nature of the wavefronts during these instants. The course of the dipole became more coherent 10 msec later when the rightward vector started to move dorsally and to the right. The excitation wave is reportedly confined almost totally to the septum at 80 msec, before terminating in the anterior free wall of the right ventricle, near the pulmonary valve. This is well represented in Figure 5 by the rightward-oriented dipole moving to the right between 75 and 90 msec, and the SMD path ending in the same region as the excitation wavefront.

For the APEX stimulation, no wavefront data are available from the literature. However, the interpretation of the general features of the SMD course is straightforward. The upward trajectory of the upward-oriented dipole is compatible with a symmetrical wavefront moving along the central axis of the heart, from the apex to the base.

As reported by Spach and Barr (1975b), the normal repolarization sequence is characterized by a predominant transmural unidirectional gradient with the endocardium being more negative than the epicardium. This was portrayed in the present study by a T wave vector oriented along the axis of the heart and almost stationary in the ventricular septal wall near the base. This stationary T wave vector also has been reported by Brody et al. (1977).

During ectopic repolarization, Spach and Barr (1975a) showed that positive potentials surround the ectopic focus whereas negative potentials appear on the opposite side of the heart where excitation terminated. This is in accord with our observation that the corresponding T wave vector was parallel to the line joining the geometrical center of the heart to the stimulation site. During the first part of the ectopic T wave, the slow speed of the SMD is also in agreement with the results for rabbit hearts (Ideker et al., 1977) showing the relative stationarity of the initial T wave dipole inside the left ventricle. The reported intramural measurements also show that the steepest potential gradients initially are around the maximum and subsequently move toward the minimum which remained in the area of terminal excitation. This was portrayed in the present study by the later shift of the T wave dipole toward the pulmonary valve for site LVW, toward the base for the APEX site and toward the left in four dogs for the RVB site.

**SMD Computations**

The precision of SMD computations is affected by different factors, some being under the control of the experimenter. One is the sampling of the body surface potential distributions. In the in vitro experiments, twenty potential measurements were sufficient to determine the six independent parameters of the SMD (Ideker et al., 1975). To investigate this problem in the dog, we conducted different computer studies on the canine torso model (Savard, 1978; Savard et al., 1978). These showed that the first four harmonics contained 98-99% of the total power of the spatial spectra for the three dipolar potential distributions and 86-93% for the five quadrupolar distributions. These first four harmonics can be estimated by the 26 electrode array. Consequently, this array was sufficient to extract the dipolar and quadrupolar components needed for the computation of the SMD parameters. However, the present array was not adequate to extract the higher order terms (octupoles) which have been shown to improve dipolar and quadrupolar estimation if they are included in the least squares fit (Cuffin and Geselowitz, 1977). Also, the SMD was recovered from simulated dipolar potential distributions on the surface of the canine torso model in the presence of random noise. The RMS position error was 1.8 cm for the present 26 electrode array, 1.2 cm for 60 equidistant electrodes, 0.9 cm for 120 equidistant electrodes, and 2 cm for 26 precordial electrodes when the signal-to-noise ratio was 30. An increased number of electrodes thus can reduce the SMD measurement error in the presence of random perturbations. However, even a large number of electrodes cannot compensate for the effects of systematic sources of error such as the electrical inhomogeneities of the thoracic volume conductor (Arthur and Geselowitz, 1970) or variations in torso geometry.

The SMD representation is limited basically to dipolar cardiac sources which are well localized. Nondipolar sources may be recognized by the presence of multiple extrema on the body surface potential maps. The use of a nondipolarity index similar to the one developed by Ideker et al. (1977) would provide an additional criterion of validity to the interpreter.

**Extension of the SMD Representation to Man**

The previously cited studies on the SMD representation in man were limited to the normal cardiac cycle and to a few subjects. In one of these studies, the location of the SMD was within the atria during the P wave and within the ventricles during the QRS and T wave (Arthur et al., 1971). These studies were done before the in vitro experiments showing that the SMD is better suited to portray the passage of an ectopic beat across the heart, or to locate a small dipolar site of electrical activity, than to represent the multiple wavefronts of the normal QRS. In the present study, the cardiac sources also were created by ectopic stimulation. But unlike the in vitro experiments, noncardiac factors such as the thoracic inhomogeneities and geometrical errors...
were present, as they would be in a clinical situation. The results showed that the initial SMD location only can give the approximate position of an ectopic focus, and that the SMD trajectory can provide some information about the location of the cardiac sources during the QRS and T wave. However, this information is easier to interpret when only one dipolar wavefront is present, such as at the beginning and end of the QRS, because the SMD location then can coincide more closely with the position of the wavefront. With two or more distinct wavefronts, the location of the equivalent dipole is a complex function of the sources, and it does not necessarily coincide with their "electric center." The SMD representation thus may be restricted to the study of well-localized cardiac sources, such as ectopic foci and preexcitation sites (Savard et al., 1979a), or other local disturbances, such as bundle branch block (Brody et al., 1974) and ischemia (Mirvis et al., 1978a; Savard et al., 1979b).

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Representation of cardiac electrical activity by a moving dipole for normal and ectopic beats in the intact dog.

P Savard, F A Roberge, J B Perry and R A Nadeau

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