Variation in cardiac position has been frequently suggested as a principal cause for the wide contrast in configuration of electrocardiograms. In contrast, both postmortem and biplane angiographic examinations have suggested that there is relatively little actual anatomical variation in the position of the heart or more particularly of the interventricular septum in healthy or diseased man. Unfortunately, orientation has in large part been assessed by inspection or assigned by assumption, and few serious attempts have been made to relate anatomical and electrical position in a quantitative fashion.

In the present study, the orientation of the interventricular septum is defined in terms of a vector normal to its surface. This representation made it possible to consider the following questions: Does the apparent direction of early QRS activity depend upon the anatomical position of the interventricular septum? Does the orientation of the whole QRS spatial vector loop depend upon the position of the septum? If anatomical and electrical positions are thus related, is variation in anatomical position the sole or even the major cause for variation in electrical position?

**Methods**

Twenty-two mongrel dogs, weighing between 7 and 14 kg, were anesthetized with sodium pentobarbital (30 mg/kg) injected intravenously. Spatial vectorcardiograms and continuous simultaneous recordings at a film speed of 36S mm per sec. of X, Y, and Z leads of a McFee-Johnston lead-field reference system were obtained as previously described. (In several of the animals a second X, or left-right lead, was recorded between ventrolateral chest grids of five electrodes each and similar in construction to the front-back grids of the Z lead.) Throughout the period of observation, the dogs remained supine and horizontal in a wooden cradle of U-shaped cross section.

Large prints were made of the pertinent QRS complexes from which spatial vector loops were reconstructed after the manner of von der Groeben. These vectorial constructions were compared with appropriate spatial vector loops recorded oscillographically for each dog (fig. 1). Upon termination of the physiological portion of the experiment with a second large dose of sodium pentobarbital, the body of each animal was placed, while in the same position in the recording cradle, in a deep freeze. After 36 to 48 hours, horizontal plane slices (using the midline dorsal contact as a vertical axis) were made by means of a bandsaw. The cardiac portion of the chest was sectioned at 2.5 cm. levels in the first nine dogs and at 1.0 cm. levels in the remainder. These sections were photographed before thawing in color and in black and white to preserve for studying the anatomical details and relationships. The cardiac portions of the slices were then removed and allowed to thaw in 10 per cent formalin solution for subsequent reference. Silastic models of the heart were made from plaster impressions of the formalin-fixed heart slices. To permit uniform treatment of the data, models from the first nine dogs were repositioned within a plastic grid using the photographs for reference, and careful measurements were made of the displacement of points on the right septal surface of the interventricular septum.
from sagittal and frontal reference planes. For the remainder (those sectioned at 1.0 cm. intervals), the surface of the right aspect of the septum was defined from tracings of the photographs of the horizontal slices (fig. 2).

Seven dogs were subjected to thoracotomy during which sutures were placed high and low on the dorsolateral aspect of the left ventricular free wall and joined to form a bridle which passed ventral to the heart and through the right anterior chest wall, there to be secured by buttons. In each instance, the chest was closed, air was aspirated, and the wounds were allowed to heal. After at least five days, each of the animals was brought back to the laboratory, and new series of recordings were made before and after rotation of the heart was accomplished by withdrawing the guy sutures for a length of approximately 6 cm. in each case and securing them to the chest wall in that position.

As shown in figure 2, the spatial coordinates for spaced horizontal and vertical chords were averaged and represented by a vector quantity normal to the average surface and proportional in magnitude to the size of the right septal surface. This vector was called the right septal surface vector, or more briefly, the anatomical vector. A line directed from the highest (most cephalic) point to the lowest (most caudal) point on the ventral margin of the right septal surface was designated the margin vector and used to determine the degree of rotation of the right septal surface about the anatomical vector normal to it.

The equations of rotational transformation aligning the anatomical vector with the negative arm of the X-axis were derived from the follow-
VENTRICULAR DEPOLARIZATION

ing trigonometric relationships in which the Cartesian coordinates of the anatomical vector are designated \( x_a, y_a, \) and \( z_a \), and those of the margin vector are designated \( x_m, y_m, \) and \( z_m \):

\[
\tan \phi = \frac{z_a}{x_a}, \tag{1}
\]

\[
\tan \omega = \frac{y_a}{\sqrt{x_a^2 + z_a^2}}, \tag{2}
\]

\[
\tan \rho = \frac{x_m \cos \phi + z_m \sin \phi}{y_m \cos \omega - x_m \sin \phi \sin \omega + z_m \sin \phi \sin \omega}. \tag{3}
\]

The angle \( \phi \) (azimuth) was read from the left axilla toward the sternum positive or toward the dorsum negative; the angle \( \omega \) (altitude) was measured as elevation from the horizontal plane—toward the head positive or toward the tail negative. The angle \( \rho \) (twist or rotation) was the angle in the last stage of transformation necessary to rotate the septum about the anatomical vector (now also the new X-axis) to make the sagittal projection of the ventral septal margin vector parallel with the new Y-axis. The Cartesian coordinates of any point, \( P \), of previous coordinates \( x, y, \) and \( z \) were designated after rotational transformation \( x', y', \) and \( z' \):

\[
x' = -x \cos \phi \cos \omega - y \sin \omega + z \sin \phi \cos \omega, \tag{4}
\]

\[
y' = -x (\cos \phi \sin \omega \cos \rho + \sin \phi \sin \rho) + y \cos \omega \cos \rho + z (\sin \phi \sin \omega \cos \rho - \cos \phi \sin \rho). \tag{5}
\]

\[
z' = +x (\cos \phi \sin \omega \sin \rho - \sin \phi \cos \rho) - y \cos \omega \sin \rho - x (\sin \phi \sin \omega \sin \rho + \cos \phi \cos \rho). \tag{6}
\]

The polar vector of the QRS spatial vector loop was determined from planimetric values for the areas of the sagittal, horizontal, and frontal plane projections (as constructed).\(^\text{10}\) Orientations of both anatomical and electrical vectors were plotted in terms of azimuth and altitude on a sphere of unit radius (fig. 3A) and later more conveniently on Aitoff's equal area projection of the sphere (fig. 3B). Standard deviations of orientation from the mean were computed in degrees of arc of a great circle of the unit sphere,\(^\text{11}\) we found a standard deviation from the mean of only 14.0 degrees of arc of great circle. The circles projected on the maps in figures 3, 4, and 6 all have radii of 2 standard deviations.

ORIENTATION OF THE POLAR VECTOR OF THE QRS SPATIAL VECTOR LOOP

Also shown in figure 3 are the orientations of the polar vectors from 22 normal dogs. The \( x, y, \) and \( z \) coordinates of the polar vector were determined in each instance by the planimetric measurement of the areas respectively of the sagittal, horizontal, and frontal projections of the spatial vector loops.\(^\text{10}\) The mean direction of the polar vector of the spatial vector loop was 14.8 degrees azimuth and 20.0 degrees altitude, with a standard deviation of 16.6 degrees of arc.

ORIENTATION OF THE 10-MSEC. VECTOR OF THE QRS SPATIAL VECTOR LOOP

The central group of small squares shown on the globe and on the map in figure 3 represents the direction taken by the QRS vector in each of the 22 normal dogs at 10 msec after the onset of ventricular depolarization. Again a fairly limited distribution was found:

Results

ANATOMICAL ORIENTATION OF THE RIGHT SEPTAL SURFACE

The orientation in 15 dogs of the average vector normal to the right septal surface was ventral, to the right, and slightly headward. As seen in figure 2, the right ventricular aspect of the interventricular septum is a highly complex surface which can be described by no means as a plane. The outline of the septum on the lower slices faced generally to the right, and, as the level of section rose headward, the right septal border rotated in space to face more and more toward the sternum so that just below the level of the pulmonary valve a cord through the arc of septal surface faced not only to the front but also slightly to the left. The orientation of the control right septal vectors is shown in figure 3. The mean direction of the right septal surface vector for this normal group was 141.7 degrees azimuth (measured from the left midaxillary line and passing through the midsternal line at 90 degrees) and +20.2 degrees altitude (measured as elevation above the horizontal plane). Using Brinberg's convention of describing the deviations from the mean direction in terms of a circle on a unit sphere,\(^\text{11}\) we found a standard deviation from the mean of only 14.0 degrees of arc of great circle. The circles projected on the maps in figures 3, 4, and 6 all have radii of 2 standard deviations.
the mean direction was 92.0 degrees azimuth and -9.4 degrees altitude, or to the front and slightly tailward. The standard deviation was 18.2 degrees of arc.

**EFFECT OF MECHANICAL ROTATION OF THE HEART UPON ELECTRICAL VECTORS**

In seven dogs, sutures were placed in the left ventricular free wall and led out through stab wounds in the right chest. After a healing period of five or more days, new recordings were made and the effect of withdrawing the suture 5 or 6 cm. was noted. In figure 4, final positions of the anatomical vectors, indicated by the triangles, are generally displaced somewhat to the animals' right of normal expectation. The direction of orientation of the 10-msec. and polar vectors before thoracotomy and after mechanical rotation is indicated by the squares and circles joined by the individual lines. Actual anatomical rotation to the right was accompanied by shift of the 10-msec. vector to the right, but the effect upon the polar vector was less predictable and less pronounced. There also appeared to be a better correlation between such rotation about the longitudinal axis of the heart and rightward movement of the 10-msec. vector than between accompanying minor rotation about the transverse axis of the heart and change in altitude of the 10-msec. vector (fig. 4).

**EFFECT OF PLACING THE ANATOMICAL VECTOR IN A STANDARD POSITION BY ROTATIONAL TRANSFORMATION OF AXES**

When rotational transformation of axes was performed mathematically (as described under Methods and as shown diagrammatically in fig. 5) so that the right septal vector lay along the negative arm of the X-axis and the sagittal projection of the margin vector lay parallel to the new Y-axis, appropriate electrical vectors for each dog were accordingly shifted as summarized in table 1. Neither the polar vectors nor the 10-msec. vectors tended to converge when the anatomical vectors were all brought together; in fact, as seen in figure 6, slight dispersion of the clouds occurred. The standard deviation for the polar vectors increased from 16.6 to 25.2 degrees of arc; and for the 10-msec. vector, from 18.2 to 22.0 degrees of arc.

**Discussion**

**ASSUMPTIONS AND LIMITATIONS OF METHODS**

Several limitations in anatomical method should be acknowledged. First, although electrical activity is expected to be more complete on the left aspect of the interventricular septum at 10 msec. after the onset of ventricular activation, we chose to define the right aspect vectorially. This was a matter of reproducibility, for, despite the fact that with similar treatment the left septal surface yielded a grouping of vectors more uniform than did the right, the investigators were reluctant to employ the derivation for the left side because of the greater element of subjective determination as to the boundaries of the septum on the left side. Examination of the outlines of the slices in figure 2 will make it clear that it is much easier to define the junction between the septum and the right ventricular free wall than the junction between the septum and the left ventricular free wall.

Another shortcoming in anatomical technique is that only one determination of anatomical position can be made per animal. It would be far more satisfactory to study the effect of mechanical rotation if the orientations both before and after rotation could be determined with certainty. Finally, death imposes a further concern in that there is possible alteration of anatomical position by postmortem change, as considered in detail by Grant. Great care was taken to minimize such effects: the body of each animal was neither removed from the cradle nor altered in position between the time of the last recording and freezing. However, it seems quite likely that there should be some change in anatomical position with cessation of the circulation: the rise in central venous pressure and the drop in arterial pressure would be expected relatively to overfill the right heart and partially to empty the left. Inspection of the slices suggested lesser cavity sizes on the left side in confirmation of such an ex-
FIGURE 2
Derivation of the vector representing the mean orientation of the right septal surface of a dog. The upper left-hand portion of the figure consists of tracings from photographs of ventricular outline from successive horizontal slices through the canine thorax at 1-cm. intervals. The limits of the right aspect of the interventricular septum have been identified at each level and connected by a cord; on each cord a vector perpendicular to the cord and equal to its length has been erected. These horizontal vectors were added vectorially, as seen on the upper right, to obtain the horizontal projection of the right septal surface vector. On the lower left, similar sagittal cords were constructed from reference points obtained from the horizontal slices, and again individual sagittal vectors were erected. These vectors were in turn added vectorially to obtain a sagittal projection of the right septal surface vector (dotted arrow in right lower corner). The magnitude then was adjusted so that the z-component of the sagittal projection equaled the z-component of the horizontal projection; thus the adjusted sagittal projection of the right septal surface vector is shown as the solid portion of the long arrow in the right lower corner.

The use of high-speed simultaneous leads made it possible to depart from the crude estimation of axis as an index of electrical position and turn to the more precise esti-
The distribution of orientations of anatomical, 10-msec. QRS, and polar QRS vectors as seen (A) on the surface of a sphere and (B) on Aitoff's equal area projection of the sphere (Chart no. 3099, U. S. Coast and Geodetic Survey). The anatomical (right septal surface) vectors (△) for 15 dogs are grouped to the animals' right front and slightly headward; the 10-msec. QRS vectors (□) for 22 dogs are directed almost straight to the animals' front; and the polar vectors (◦) for 22 dogs are directed to the animals' left just slightly headward and frontward. The x's represent means for each group, and the large circles represent the limit of 2 standard deviations from the mean (in degrees of arc of great circle).

The polar vector of the QRS spatial vector loop was derived from plane projections constructed from the same set of simultaneous complexes as that from which the 10-msec. vector had been obtained in each instance. This precaution assured us of more immediate comparability between the two different kinds of electrical vectors at the expense of minor error arising from the differences between the areas of a set of constructed projections and those of a set recorded oscillographically.

The fact that we expected transformation of axes to be a test of the degree of depend-
ence of electrical position upon anatomical position involves the assumption that the two (or three) different kinds of vectors can be referred to a common axis-frame. The lead-field system of reference was utilized here in order to minimize those effects which would detract from considering the recorded electrical activity in vectorial, and hence dipolar, terms. In retrospect, this could have been further enhanced had the entire series of experiments been obtained with multiple-component grids for the left-right lead as well as for the front-back lead. Our few observations with such a lead indicated a better correlation between the apparent septal vector (10-msec. vector) and the anatomical orientation of the septum than noted for the general group here reported.

RELATIONSHIP BETWEEN 10-MSEC. QRS VECTOR AND RIGHT SEPTAL SURFACE VECTOR

Ten msec. after the first detectable deflection of a scalar lead signaling the onset of the QRS complex is an arbitrary choice of timing for the "septal vector." The ideal time sought for was the time most likely for septal activation to be well under weigh but with minimal contamination by activation elsewhere. Review of the experimental literature to anticipate such a time would suggest an instant between 5 and 15 msec. after the beginning of the QRS with 10 msec. as a reasonable compromise. However, the reservation should be made that the 10-msec. vector probably departs in its orientation from the true mean direction of septal activation at 10 msec. according to the effectiveness of certain other variables, especially the simultaneous existence of waves of activation elsewhere in the ventricular myocardium and the field-distorting effect of having the septum caught between the two intracavitary blood masses of relatively low resistivity.

A discrepancy may also be expected between the true mean direction of septal activation and the anatomical vector of the right septal surface. While activation of the left septal surface may be largely complete by 10 msec. after QRS onset, activation of the right surface at the same instant is likely to be
not only incomplete but also rather variable in anatomical pattern.\textsuperscript{12, 14} From the available experimental evidence already cited, we may expect almost none of the basal right septal surface to have been fired as early as 10 msec. after the onset of ventricular depolarization. It is conceivable that a small lag on the left might be enough to tip the balance toward right-to-left predominance at 10 msec., but we observed no such instances.

<table>
<thead>
<tr>
<th>Vector</th>
<th>Mean azimuth (degrees)</th>
<th>Mean altitude (degrees)</th>
<th>Standard deviation (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anatomical (right septal)</td>
<td>141.7</td>
<td>29.2</td>
<td>14.0</td>
</tr>
<tr>
<td>10-msec., QRS\textsuperscript{*}</td>
<td>92.0</td>
<td>-9.4</td>
<td>18.2</td>
</tr>
<tr>
<td>Polar, QRS\textsuperscript{*}</td>
<td>14.8</td>
<td>29.0</td>
<td>16.6</td>
</tr>
<tr>
<td>Transformed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anatomical (right septal)</td>
<td>180.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>10-msec., QRS</td>
<td>186.6</td>
<td>-26.7</td>
<td>22.0</td>
</tr>
<tr>
<td>Polar, QRS</td>
<td>66.6</td>
<td>26.1</td>
<td>25.2</td>
</tr>
</tbody>
</table>

\textsuperscript{*} Sample contains recordings from 22 dogs (including the 7 later undergoing thoracotomy and subsequent mechanical rotation of the heart). The samples of normal anatomical vectors and normal transformed electrical vectors each contain data from 15 dogs.
TRANSLATING THE RIGHT SEPTAL SURFACE VECTOR TO A STANDARD POSITION

Finally, the gross departure from the flocks of both polar and 10-msec. vectors noted after mechanical rotation in one animal (fig. 4) suggests that a conduction defect may have occurred in this circumstance—there was indeed a gross change in configuration of the QRS complexes to confirm this suspicion.

It is important to note that, despite the many possible interfering factors, physically turning the septum to the right consistently turned the 10-msec. vector rightward also. That more than one simple variable was involved was indicated by the simultaneous unpredictable headward or tailward shift in the 10-msec. vector.

Rotational transformation of axes was employed to test whether the scatter of orientations of the 10-msec. vector (or of the polar QRS vector) depended solely or almost solely on the natural scatter of anatomical orientations. If so, bringing all the anatomical vectors to a common axis should have the effect of similarly bringing to a focal point the dependent electrical vectors. That such focusing did not result (fig. 6) is interpreted to mean that there were other significant variables (such as individual variation in the pattern of activation) which determine electrical position. The significance of slight increases in standard deviation of electrical vectors (unfocusing) that occurred upon transformation (fig. 6 compared with fig. 3B) were assayed by examining the ratios of variance. The change in standard deviation produced in the 10-msec. vectors was that readily expected from chance rearrangement of the group. However, the change in standard deviation for polar vectors was of the order expected by random rearrangement in less than 10 but more than 5 times out of 100. This suggested a lesser degree of anatomical dependence for the polar vector, perhaps because of the many more opportunities for variation in the temporospatial pattern of activation throughout the whole QRS spatial vector loop than during the instant of the 10-msec. vector.

Summary

Exact anatomical orientation of the interventricular septum was compared with apparent direction of electrical activity during ventricular depolarization in 22 dogs. In 15 control animals, the mean orientation of a vector normal to the right septal surface was toward the front, to the right, and slightly headward. The mean orientation of the 10-
The effect upon the relative orientation of electrical vectors (10-msec. and polar QRS vectors) of rotational transformation bringing all anatomical vectors into a common orientation along the negative X-axis in 15 dogs. The anatomical vectors are shown grouped at the end of the X-axis as a single point ($\Delta$). Note that the size of the 2-standard-deviation circle of the 10-msec. QRS vectors (○), and especially of the polar QRS vectors (●), is greater than that of the corresponding limits in figure 5. (See text for details.)

msec. vector (QRS) was almost directly toward the front and slightly tailward. The mean orientation of the polar vector was to the left, slightly to the front, and slightly headward. The values for each of these means were obtained in spherical coordinates: anatomical vector—141.7 degrees azimuth, 20.2 degrees altitude; 10-msec. vector (QRS)—92.0 degrees azimuth, -9.4 degrees altitude; and polar vector—14.8 degrees azimuth, 20.0 degrees altitude. In 7 dogs, rotation of the heart to the right by means of previously implanted guy sutures consistently moved the 10-msec. vector to the right also, but there was simultaneous unpredictable deviation either headward or tailward of the electrical vector. Polar vector shift was not consistent.

Rotational transformation of axes for each dog, bringing the vector of the right septal surface into coincidence with the negative X-axis, did not bring to a focus the scatter of orientations of either group of electrical vectors, indicating that variation in electrical position depends upon other factors in addition to variation in anatomical position.

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