A Comparative Study of Spatial Vectorcardiograms Obtained with the Equilateral Tetrahedron and a “Corrected” System of Electrode Placement

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Spatial vectorcardiograms of a group of normal young adults, recorded with two systems of electrode placement, have been studied. Those recorded with the equilateral tetrahedron as the reference system were similar to records previously described and had QRS-loops of two configurations. Those recorded with a method of lead placement designed to reduce the errors inherent in the commonly used reference frames had greater uniformity of form and orientation of both the QRS and T-loops.

It is well known that many assumptions inherent in representing the human body as a regular geometric figure are only approximations. The concept of so representing the body has been extremely useful in electrocardiography despite errors introduced by these simplifying assumptions, but it is nevertheless desirable to eliminate or minimize these errors. This is especially important in studies of the spatial vectorcardiogram which it is hoped will extend the range of usefulness of electrocardiography.

By application of the reciprocity theorem of Helmholtz to experimental data obtained with fluid mappers representing the body, McFee and Johnston have designed a system of electrode placement which appears promising as a method of reducing some of the errors in electrocardiography.1-3 Briefly stated, this “corrected” lead system depends on effectively modifying the form of the lead fields in the body by the use of multiple electrodes at such sites that the fields will be altered in the desired direction. For example, the lead field of standard lead I is effectively modified by connecting the electrode on the right arm to an electrode on the right side of the chest, and that on the left arm to an electrode on the left side of the chest, with each electrode in series with a large resistance. The studies of McFee and Johnston indicate that the lead field of the two electrodes on the sides of the chest has characteristics which tend to cancel the undesirable features of the lead field of standard lead I.

A combination of electrodes at sites chosen to modify the anteroposterior lead field in the sagittal plane in the desired direction has also been suggested by these workers. This consists of multiple chest electrodes placed in front of, and behind, the heart, and the horizontal component in the sagittal plane obtained with this lead system represents the potential difference between the anterior and posterior electrodes.

The present study has no direct bearing on the validity of either of the lead systems employed. The purpose of the study was to obtain clinical experience with the recently suggested lead system, and to compare vectorcardiograms and electrocardiograms obtained with this system and those obtained with the equilateral tetrahedral method of electrode placement. This appeared desirable, both as a foundation for possible future clinical application of the new system and as an aid in defining the potential usefulness of the system.

Materials and Methods

Studies were made on 75 male subjects in the age range of 18 to 35 years. A medical history, physical
examination, teleroentgenogram of the chest and electrocardiogram, including standard and unipolar limb leads and precordial leads $V_1$ through $V_6$, were obtained on each subject. None of the subjects had evidence of cardiovascular disease.

Spatial vectorcardiograms were obtained on each subject using both the equilateral tetrahedral system of electrode placement and the "corrected" leads devised by McFee and Johnston to obtain the horizontal ($x$ and $z$) components in the frontal and sagittal planes. Leads $V_9$ was utilized as the vertical ($y$) component of the vectorcardiogram with both electrode systems.

With the equilateral tetrahedron as a reference frame, frontal and left sagittal plane projections of the vectorcardiogram were recorded simultaneously from two cathode ray oscilloscopes. Superior plane and frontal stereoscopic views obtained by the method of Cronvich and coworkers were also recorded. Standardizing factors appropriate to this reference frame were employed. These were such that 1 mv introduced in the vertical deflecting circuits produced a deflection of 1.7 units and when introduced in the horizontal deflecting circuits produced a deflection of 1 unit on the oscilloscope used to record the frontal and 1.2 units on the oscilloscope used to record the left sagittal plane projection. For the stereoscopic views the standardizing factors were such that 1 mv introduced in the horizontal deflecting circuits produced a deflection of 1 unit and introduced in the vertical deflecting circuits a deflection of 1.7 units on both oscilloscopes. With this electrode system, connections were such that relative positivity of the left arm in the frontal plane and of the back electrode in the sagittal plane produced a deflection of the beam to the left (the observer's right) and relative positivity on the left leg produced a downward deflection in both frontal and sagittal planes.

Frontal and left sagittal plane projections were recorded simultaneously, using the "corrected" lead system. As employed in this study, the horizontal component ($x$) of the frontal plane projection was furnished by a lead composed of electrodes on the left arm and a point on the left midaxillary line at the level of the ensiform cartilage, each in series with a large resistor and connected together, and a similar pair of electrodes on the right arm and the right side of the chest. The sagittal component ($z$) of the vectorcardiogram was represented by the potential difference between two banks of nine electrodes each, placed opposite each other on the anterior and posterior surfaces of the chest. The electrode banks were so placed that the center of the posterior bank was located 2 cm. to the left of the seventh dorsal vertebra. Each electrode bank measured 12 by 12 cm. and each electrode was German silver and measured 1 by 1 cm. Each electrode was in series with a large resistance and all electrodes comprising each bank were connected together beyond the resistors. The vertical component of both frontal and sagittal projections was furnished by lead $V_9$.

Standardizing factors employed with the "corrected" method of electrode placement were such that 1 mv. introduced in the horizontal deflecting circuits produced a deflection of 1 unit on both oscilloscopes and 1 mv. introduced in the vertical deflecting circuits produced a deflection of 1.7 units. With this electrode combination, relative positivity of the electrode pair on the left arm and left side of the chest and of the electrode bank on the posterior surface of the chest produced a deflection of the electron beams to the left (the observer's right), and relative positivity of the left leg produced a downward deflection.

The large resistances in series with the multiple electrodes employed in the "corrected" lead system act to average the potential at the electrode sites without distorting the electric field by production of large isopotential areas. To adequately accomplish this, it is necessary that these resistances be approximately equal. Since the skin resistance at each electrode site acts in series with a resistor in the external network it is desirable that the value of the skin resistance be low relative to the network resistors. Inequalities in the values of skin resistance are minimized if the external network resistances are high. Thirty-five of the records included in this study were obtained with a 50,000 ohm resistor in series with each electrode site making up the "corrected" leads. For the remaining 40 records, each resistor had a value of 1 megohm which further reduced the effect of unequal skin resistances at the electrode sites.

The amplifiers employed in this study were standardized by application of the calibration voltage to the cathodes of the input tubes. Using this method of calibration with the resistor networks employed in the "corrected" leads, it is necessary to consider the effect of the networks on the magnitude of records if they are to be compared to those obtained with other reference frames. The effect of the resistor networks on the magnitude of the records can be expressed as:

$$eo = \sum Ri$$

where:

- $eo$ = effective voltage delivered to amplifier
- $ei$ = effective voltage at the electrodes
- $Ri$ = input impedance of amplifiers
- $Rex$ = effective external resistances in the network

The amplifiers employed in this study had an input impedance of 4.7 megohms in the relevant frequency range. With the standardizing factors employed, the horizontal component of the frontal plane projection of the 35 records obtained with 50,000 ohm resistors in the networks was 0.5 per cent less than the proper value. The horizontal
component in the sagittal plane of these records was 0.2 per cent less than the proper value. In the 40 records obtained with 1 megohm resistors in the networks, the horizontal component in the sagittal plane was 2 per cent less than the correct value. For the purposes of this study, these errors were considered insignificant and no corrections were made. The horizontal component of the frontal plane projections in the records obtained with 1 megohm resistors in the networks was 10 per cent less than the proper value, and measurements of maximal QRS and T vectors from these records were corrected geometrically.

In all records, time was indicated by interrupting the oscilloscopic trace 400 times per second, and shaped segments of the trace with the blunt end of each segment in the lead indicated the inscription direction.

Each of the plane projections and the stereoscopic views of the vectorcardiogram were inspected and the general contour, magnitude and orientation of the QRS- and T-loops were noted. The direction of inscription of the QRS-loops in frontal and sagittal plane projections was also noted. Three-dimensional wire models representing each QRS-loop recorded with both electrode systems were constructed to conform to the plane projections. The magnitude and orientation in a triaxial reference system of the longest vector of the QRS- and T-loops were measured in the frontal and left sagittal plane projections. In the case of the left sagittal plane projection the \( \pm 180 \) degree axis of the triaxial reference system was considered to be located anteriorly. Finally the maximal extension of the QRS-loop behind a vertical line through the isoelectric point was measured in millivolts.

All observations and measurements made on vectorcardiograms obtained with the equilateral tetrahedron reference frame were compared with those on records made with the "corrected" lead system. Electrocardiograms showing simultaneous horizontal \((x \text{ and } z)\) and vertical \((y)\) components of the frontal and sagittal plane projections of the vectorcardiograms recorded with the two lead systems were also compared.

**RESULTS**

**QRS-Loop**

(1) **Contour.** It has been previously reported that the QRS-loops of normal subjects in the age group represented in this series, recorded with the equilateral tetrahedral reference frame, could be divided into two groups on the basis of spatial configuration.\(^5\) These loops were designated as "type 1" when they were elliptoid figures whose maximum width was approximately one-third of the greatest length, and "type 2" when the loops were characterized by a greater enclosed area behind the isoelectric point and had a roughly circular spatial outline. In the reported series, 88 per cent of the QRS-loops were of the "type 1" and 12 per cent of the "type 2" configuration.

Similar results were obtained in the present series of QRS-loops recorded with the tetrahedral electrode placement. Sixty-three (84 per cent) of the QRS-loops had elliptoid spatial configurations and were classified as "type 1". Twelve (16 per cent) of the loops had the configuration previously designated as "type 2" with roughly circular spatial outlines and large enclosed areas behind the isoelectric point.

The QRS-loops of vectorcardiograms obtained with the "corrected" lead system showed no such division into "types". Variations in spatial orientation and minor variations in contour resulted in differences in the form of planar projections of the loops, but the major features of spatial configuration were similar.

The vectorcardiograms of 58 subjects whose routine electrocardiograms showed a normal electrical axis or left axis deviation had only minor differences in the contour of frontal plane projections of the QRS-loops recorded with the tetrahedral and "corrected" lead systems. Definite differences in the configuration of the frontal plane projection of the QRS-loops of the remaining 17 subjects were present. The routine electrocardiograms of all of these subjects showed a moderate or marked right axis deviation with deep S waves in lead 1, and the frontal plane projections of the QRS-loops enclosed large areas to the right of the isoelectric point. In contrast the same projection of the QRS-loops recorded with the "corrected" lead system enclosed smaller areas to the right of the isoelectric point, and the "corrected" lead I of these subjects had only shallow S waves. These findings are illustrated in figure 1. The frontal plane projection of a vectorcardiogram recorded with the equilateral tetrahedron and its horizontal scalar component (lead 1) are shown in figure 1A. It may be noted that this
Fig. 1. A shows the frontal plane projection of a vectorcardiogram with the equilateral tetrahedron from a subject whose electrocardiogram showed right axis deviation. Standard lead I of the electrocardiogram is also shown. In B the frontal plane projection of the same subject’s vectorcardiogram recorded with the “corrected” lead system is shown together with its horizontal scalar component.

projection of the QRS-loop enclosed a large area to the right of the isoelectric point and that lead I has a deep S wave. Figure 1B shows the frontal plane projection and the horizontal scalar component of the vectorcardiogram of the same subject recorded with the “corrected” electrode placement. In this vectorcardiogram the area to the right of the isoelectric point is smaller and only a small S wave is present in “corrected” lead I.

The sagittal plane projections obtained with the “corrected” leads were remarkably similar to each other, and differed considerably from those recorded with the tetrahedron.

The “type 1” QRS-loops recorded with the tetrahedron had elliptoid configurations in the sagittal plane while those classified as “type 2” had more complex contours in this plane with a large enclosed area behind the isoelectric point. The general form of the sagittal plane projection of QRS-loops recorded with the “corrected lead” systems was roughly triangular. The initial and terminal portions of the loop formed one side and the mid portions of the other two sides of this figure. The major variations of contour of the “corrected” QRS-loop in the sagittal plane are illustrated in figure 2.

The similarity of QRS-loops recorded with the “corrected” lead system was most apparent in the three dimensional models constructed to conform to the plane projections of the vectorcardiogram. The finding is best illustrated by comparing the contour of the “corrected” QRS-loops of two subjects whose QRS-loops obtained with the tetrahedral reference frame were of the “type 1” and “type 2” varieties. Figure 3 shows an example of such records. In figure 3A the frontal and sagittal plane projections of a “type 1” QRS-loop obtained with the tetrahedral reference frame are shown.

Fig. 2. The major variations in contour of the left sagittal plane projections of vectorcardiograms recorded with the “corrected” system of lead placement are illustrated. A shows a form in which the maximal vector is directed posteriorly, while in B this vector is directed downward and in C is directed forward.
above these views of the same subject’s vectorcardiogram recorded with the “corrected” leads. Figure 3B shows similar views of a “type 2” QRS-loop recorded with the tetrahedron and those recorded on the same subject with the “corrected” leads. The greater similarity of vectorcardiograms obtained with the “corrected” leads is apparent.

(2) Orientation. Variations in orientation about the anteroposterior, transverse and longitudinal axes of the loops were found in records obtained with both reference frames. With present methods it is difficult to quantify variations in orientation of spatial vectorcardiograms. The direction of the maximal QRS vectors in frontal and sagittal planes is not adequate to indicate the orientation of records having variable form. Wide variations in the orientation of the maximal vectors of records obtained with both reference systems were found but the general impression from simple observation of the planar projections and the spatial models was that less variation in overall orientation was encountered in the records obtained with the “corrected” lead system.

(3) Magnitude. The major difference in the magnitude of QRS-loops obtained with the tetrahedral and the “corrected” lead systems was in the area enclosed by the sagittal plane projection. Considerably greater areas were enclosed in the “corrected” sagittal projections and this difference was reflected in measurements of the magnitude of maximal QRS vectors. The average maximal vector in the sagittal plane projection of records obtained with the tetrahedron was 0.78 mv. while that in records obtained with the “corrected” lead system was 1.12 mv. This difference in the magnitude of the sagittal plane projection of the QRS-loops obtained with the two electrode systems was also reflected in the measurements of the “maximal posterior extent” by which is meant a measurement from the most extreme posterior portion of the loop to a vertical line through the isoelectric point of loops. The “maximal posterior extent” of QRS-loops recorded with the tetrahedron ranged from 0 to 1.15 mv. with an average value of 0.32 mv. while that of records obtained with the “corrected” leads ranged from 0.22 mv. to 2.4 mv. and averaged 0.92 mv.
**T-Loops**

One of the marked differences in the records obtained with the two reference frames was in the contour, orientation and magnitude of T-loops in the sagittal plane projection. In records obtained with the tetrahedron the T-loops were ellipsoid or roughly circular outlines and were directed downward and either slightly forward or backward. T-loops in the sagittal projection of records obtained with the “corrected” lead system were uniformly ellipsoid in outline, were directed anteriorly and were larger than T-loops obtained with the tetrahedron. The average magnitude of the maximal vector of T-loops recorded with the tetrahedron was 0.29 mv. in the frontal and 0.19 mv. in the sagittal plane, while that of T-loops obtained with the “corrected” electrode placement was 0.34 mv. in the frontal and 0.53 mv. in the sagittal plane. Examples of the contour of T-loops obtained with the two electrode systems may be seen in figures 1 to 3. In both contour and orientation, T-loops recorded with the “corrected” lead system differed less from one another than did T-loops recorded with the equilateral tetrahedron.

**Discussion**

The results of this study do not constitute direct evidence for the superiority of either of the electrode systems employed. It is very likely that significant errors in sampling the components of the electric field produced by the heart occur with both systems. However the studies of McFee and Johnston indicate that the electrode combinations they have suggested operate to reduce these errors. The concept of utilizing multiple lead fields whose undesirable features tend to cancel appears to be a potentially important one and clinical observations with electrode combinations based on this concept seem to be indicated.

In this study electrocardiograms and vectorcardiograms obtained with the new electrode combinations have been compared with those recorded with the equilateral tetrahedral reference frame. Differences in configuration, orientation and magnitude were all encountered.

The configurations of vectorcardiograms recorded with the equilateral tetrahedral reference frame were of two general types, as has been previously reported, while the major features of spatial configuration of vectorcardiograms obtained with the “corrected” lead systems were similar. This finding is of particular interest since Gardberg’s studies concerning the effect of eccentricity of the heart on the electrocardiogram and vectorcardiogram led him to suggest that the division of vectorcardiograms recorded with the tetrahedral method of electrode placement into two groups is an artefact related to the proximity of an electrode on the back to the heart.6

The vectorcardiograms and electrocardiograms obtained with the “corrected” lead system on subjects whose routine electrocardiograms showed right axis deviation are also of special interest. Both the form and orientation of these QRS-loops differed less from the remainder of records obtained with this lead system than did those obtained with the tetrahedron from other QRS-loops recorded with the same reference system. The conventional standard lead I of these subjects showed large S waves, while in the “corrected” lead I of the same subjects the S waves were small as is more common in lead I of normal subjects. Although it could not be quantitated in this study there appeared to be less variation in spatial orientation of QRS-loops recorded with the “corrected” lead system than in those obtained with the equilateral tetrahedron. There was definitely less variation in orientation and contour of T-loops obtained with the “corrected” lead system than in those recorded with the tetrahedral electrode placement.

The finding of greater uniformity among vectorcardiograms obtained with the lead system suggested by McFee and Johnston than in the records obtained with the tetrahedron, while not direct evidence, is consistent with the view that less distortion of the electric field of the heart is associated with use of these “corrected” leads. Studies designed to quantitate the errors involved in the use of multiple lead fields to obtain components of the “heart vector” and to define the optimal
electrode combinations, as well as further clinical studies of both normal and abnormal subjects, will be necessary to assess the importance and usefulness of the concept involved.

Summary

Spatial vectorcardiograms of 75 normal young males, obtained with the equilateral tetrahedral reference frame and with a “corrected” lead system suggested by McFee and Johnston, have been compared. The study was undertaken to provide clinical experience with the latter lead system and has no direct bearing on the validity of that system.

As previously reported, QRS-loops recorded with the tetrahedral reference frame could be divided into two groups on the basis of spatial configuration. Orientation about all axes of the loops varied. T-loops in records recorded with the tetrahedron were elliptoid or roughly circular and the maximal vectors were directed downward, to the left and either slightly forward or backward.

In contrast the QRS-loops recorded with the “corrected” lead system showed considerable similarity to each other and appeared to have less variation in spatial orientation. The area enclosed by the sagittal plane projection of the QRS-loops was much greater in records obtained with this reference system than in those recorded with the tetrahedron. T-loops recorded with this reference system were uniformly long elliptoid outlines directed to the left downward and forward.

Summario in Interlingua

Duo systemas de placentamento del electrodos eseva usate in le registration de vectocardio grammas spatial ab un gruppo de normal juvenes adults. Le registrationes obtenite con le uso del equilatera tetrahedro como systema de referentia eseva simile a previemente describite registrationes e exhibiva ansas QRS de duo configurationes. Le registrationes obtenite con le uso de un placentamento del derivaciones destinatione a reducir le errores inherente in le currente systemas de referentia exhibiva un plus uniforme configuration e orientation del ansas QRS e etiam del ansas T.

References

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