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Lead Selection, Cardiac Axes, and

Interpretation of Electrocardiograms in Beef Cattle

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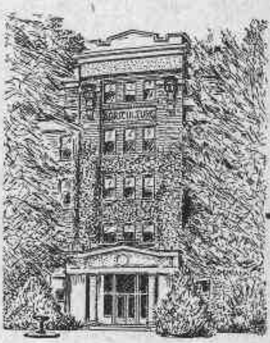

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Introduction

Studies on the electrocardiology of man are exceedingly numerous, as are basic investigations using experimental animals, such as cats, dogs, and rabbits. Only a small number of papers are concerned with electrical events in the hearts of ruminants. Lepeschkin (22, 23) has compiled comprehensive reviews on electrocardiographic literature. These include studies on ungulate electrocardiography in which wave configurations, axis orientation, and electrode placements are discussed as well as pertinent anatomical and physiological relationships. Our literature review has disclosed 23 papers concerned with cattle, and only two of these include data on beef cattle.

Study and practice of electrocardiology involves many methods of procedure and interpretation, as well as differing explanatory theories proposed and utilized by various groups and schools. International electrocardiology commissions have formally recognized basic systems of nomenclature, and terminology in this paper will follow international standards outlined in Dimond (13) and in Burch and Winsor (8).

The purpose of this paper is to present electrocardiograms taken with a wide variety of leads; to discuss selection of leads so that interpretable electrocardiograms may be obtained from beef cattle; to determine orientation of the P, QRS and T axes in beef cattle and changes in the QRS axis with increase in size from 500 to 800 pounds weight. An outline of special terminology required in discussion of electrocardiograms is given along with a brief historical summary of electrocardiographic data collected on beef cattle.

Basic Electrocardiographic Concepts and Definitions

When any animal or plant tissue becomes active or is injured, the active or injured portion of tissue becomes electrically negative with respect to inactive or uninjured tissue. In the heart, the electrical activity developing during each contraction is of such a magnitude that deflections can be induced by connecting almost any two points of the body with a sensitive galvanometer. Characteristics of the galvanometer deflection vary with distance of the electrodes from the source of electrical potential, magnitude of the potential, and direction of development of the electrical potential. Usually a pattern of five waves or deviations from the base line (labeled for convenience P, Q, R, S and T) can be recognized. Sometimes more than five and sometimes less than five waves are obtained from a given lead. Examples of electrocardiographic patterns obtained from a beef calf are given in Figures 1-3. These indicate that a wide variety of electrocardiograms (EKG) can be obtained from a single animal.

EKG Leads

Most of the variation in EKG patterns of Figures 1 to 3 can be explained on basis of leads selected. Any set of two connections from the body to the galvanometer or recording instrument constitutes a lead. Leads are classified as *bipolar, unipolar* or *pooled,* and *augmented unipolar.* Experience in taking electrocardiograms in man has led to routine placement of five electrodes. One electrode is placed on each limb just above the wrist or ankle joint and the fifth on the chest. The electrode on the right rear limb is connected to the ground.

The leads generally used in our study of beef calves with their positive and negative instrument connections are labeled as follows:

I. L or Limb Series

A. Bipolar Leads

	Negative Connection	*Positive Connection*
I	Right forelimb	Left forelimb
II	Right forelimb	Left hind limb
III	Left forelimb	Left hind limb
CR	Right forelimb	Chest
CF	Left hind limb	Chest
CL	Left forelimb	Chest

B. Unipolar or Pooled Leads

V	Right forelimb Left forelimb Left hind limb	Chest

C. Augmented Unipolar Leads

aVR	Left forelimb Left hind limb	Right forelimb
aVL	Right forelimb Left hind limb	Left forelimb
aVF	Right forelimb Left forelimb	Left hind limb

While the electrodes are routinely placed on the limbs and chest wall, they may be placed elsewhere. The chest electrode is regularly moved to different points on the body surface. We have used many positions for the chest electrode, and 11 merit identification. A rubber chest strap was placed around the animal behind the front legs at about the 6th rib (Figure 4A). The chest lead electrode was then moved along this strap to give 10 chest positions (Figure 4D) which are approximately as follows:

C_1 or V_1	Right sternal margin near 7th rib.
C_2 or V_2	Center of sternum near 7th rib.
C_3 or V_3	Left sternal margin near 7th rib.
C_4 or V_4	Under the left olecranon between 5th and 6th rib.
C_5 or V_5	Between 6th and 7th rib on a level with the tuberculum majus (point of the shoulder) of the left scapula.
C_7 or V_7	Between 7th and 8th rib posterior to the dorsal angle of left scapula.
C_9 or V_9	Between 7th and 8th rib posterior to the dorsal angle of right scapula.
C_{11} or V_{11}	Between 6th and 7th rib on a level with the tuberculum majus of the right scapula.
C_{12} or V_{12}	Under the right olecranon between 5th and 6th rib.

The chest electrode was also routinely moved to a prescapular position (Figure 4) identified as C_8 or V_8 and to a dorsal midline position (Figure 4C and 4D) near the last thoracic vertebra and identified as C_T or V_T. Possible combinations of the chest electrode with the right forelimb electrode are identified as CR_1 (chest position one and right forelimb), CR_2, CR_3, CR_4, CR_5, CR_7, CR_9, CR_{11}, CR_{12}, CR_8, and CR_T. A similar set of eleven leads, CL_1, CL_2, CL_3, CL_4, CL_5, CL_7, CL_9, CL_{11}, CL_{12}, CL_8, CL_T, are obtainable for the chest electrode in combination with the left forelimb electrode and another set of eleven, CF_1, CF_2, CF_3, CF_4, CF_5, CF_7, CF_9, CF_{11}, CF_{12}, CF_8, CF_T, from combinations of chest electrode with the left rear limb electrode.

It has been advantageous to move the left rear limb electrode to the dorsal midline at the thoraco-lumbar border position (Figure 4C) for a T-series, and then to a midline prescapular position (Figure 4B) for an S-series. An X (cross-section) series in which forelimb electrodes were moved to slight depressions on the surface of the calf behind the dorsal angle of the right and of the left scapulae (V_7 and V_9 positions) while the left hind limb electrode was placed on the left sternal margin (V_3 position) was also studied. The X-series

(Figure 4D) provides an inverted S-series, but the plane of the X-series is at a 15° angle to the S-series. There thus are available the following series of leads:

II. T or Thoracolumbar Series

A. Bipolar Leads

	Negative Connection	*Positive Connection*
T-I	Right forelimb	Left forelimb
T-II	Right forelimb	Dorsal thoracolumbar border
T-III	Left forelimb	Dorsal thoracolumbar border

B. Augmented Unipolar Leads

T-aVR	Left forelimb Thoracolumbar border	Right forelimb
T-aVL	Right forelimb Thoracolumbar border	Left forelimb
T-aVF	Right forelimb Left forelimb	Thoracolumbar border

III. S or Scapular Series

A. Bipolar Leads

	Negative Connection	*Positive Connection*
S-I	Right forelimb	Left forelimb
S-II	Right forelimb	Prescapular position
S-III	Left forelimb	Prescapular position
S-CR	Right forelimb	Chest
S-CF	Prescapular position	Chest
S-CL	Left forelimb	Chest

B. Unipolar or Pooled Leads

S-V	Right forelimb Left forelimb Prescapular position	Chest

C. Augmented Unipolar Leads

S-aVR	Left forelimb Prescapular position	Right forelimb
S-aVL	Right forelimb Prescapular position	Left forelimb
S-aVF	Right forelimb Left forelimb	Prescapular position

IV. X or Cross-sectional Series

A. Bipolar Leads

	Negative Connection	*Positive Connection*
X-I	Dorsal angle of right scapula	Dorsal angle of left scapula
X-II	Dorsal angle of right scapula	Left sternal margin near 7th rib
X-III	Dorsal angle of left scapula	Left sternal margin near 7th rib

B. Augmented Unipolar Leads

X-aVR	Dorsal angle of left scapula Left sternal margin near 7th rib	Dorsal angle of right scapula
X-aVL	Dorsal angle of right scapula Left sternal margin near 7th rib	Dorsal angle of left scapula
X-aVF	Dorsal angle of right scapula Dorsal angle of left scapula	Left sternal margin near 7th rib

The *bipolar* leads are obtained by pairing electrodes from two points on the body. The *unipolar* leads were originally designed by Wilson to measure the voltages present at *one* particular spot on the body with respect to a nonfluctuating reference point. Each limb electrode was connected through a 5,000 ohm resistance to the negative terminal of the recording instrument; thus a pooling of the potentials from the three leg electrodes is effected at the negative terminal of the recording instrument. Since its original purpose was to measure voltage at a single point, the symbol V was used to designate this pooled lead. In the Goldberger system extra resistances are not introduced to the circuit, and only two leads are pooled at the negative terminal of the recording instrument. The two connections pooled have been tabulated above for various augmented unipolar leads (Dimond: 13, p. 47).

Pooling of the three limb electrodes provides the negative connection with the recording instrument in the Wilson V leads. Positive connection to the instrument is made through a fourth electrode which can be placed anywhere on the body. If the fourth electrode is placed on the right forelimb, left forelimb, or left hind limb (but always discretely separate from the components of the pooled lead), EKG complexes recorded are small. Hence Goldberger designed the *augmented unipolar leads* for the limbs which superseded the Wilson *unipolar limb leads,* but did not supersede the Wilson unipolar chest leads. Because the electrocardiograms with limb leads from the Goldberger system were more ample than those from the Wilson unipolar system, the symbol *a* was prefixed to indicate *augmented,* and the symbol *V* was retained for voltage.

In defining the various leads, several symbols have been used whose meaning may or may not be obvious. Terms R, L, F, and C refer respectively to right forelimb, left forelimb, left hind limb, and chest. V represents a voltage lead either unipolar or augmented unipolar. T defines an electrode on the mid-dorsal thoraco lumbar border, S an electrode between and anterior to the scapulae, C_T the chest electrode in the T or mid-dorsal thoraco lumbar position, and X refers to a set of three electrodes, at the left sternal margin and at the dorsal angles of right and left scapulae, giving a cross-sectional plane.

Dipole Theory of Cardiac Potentials

In accordance with a theory proposed by Lewis (Best and Taylor, 7), as electrical potential develops in the heart, minute areas of cardiac muscle become electrically negative to corresponding areas lying immediately adjacent. Thus microscopical electric batteries, or dipoles are visualized which constitute developing electrical activity. This theory considers the heart to have innumerable units in which action potentials are developed having different directions at any given instant, and from one instant to the next. These dipoles sometimes will neutralize and sometimes reinforce one another. At any given instant the innumerable microscopic dipoles can be considered to be equivalent to a single resultant dipole whose magnitude and direction determines degree of deflection obtained by connecting a recording instrument to any two body points.

P, Q, R, S, or T waves represent periods where there has been considerable reinforcement of dipoles to yield a resultant with detectable magnitude and definite direction. When the microscopic dipoles mutually cancel one another the resultant potential is zero, and connections to the recording instrument are *isoelectric,* or *do not* yield a deflection of the recording instrument.

When the resultant potential is not zero, the greatest deflection of the recording instrument is obtained when electrodes are as close as possible to the theoretical resultant dipole and placed along the dipole axis. At approximately equal distances of the electrodes from the heart, greatest potential is developed when the line through the electrodes is parallel to the axis of the resultant dipole and least if this line is perpendicular to the axis of the resultant dipole. When the axis through the electrodes is perpendicular to the dipole axis, the potential difference recordable is negligible or indeterminable, and electrodes can be considered as isoelectric. Following the T wave is a period when the heart may be considered as electrically quiescent. The point to which the recording instrument is adjudged during this quiescent period is taken as the *isoelectric* or *zero* level of cardiac potential.

Polarization Theory of Cardiac Potentials

The resting state of extra- and intra-cellular interfaces in the heart is frequently visualized with positive ions arranged on one side and negative ions arranged on the other side of the interfaces. In the resting state microscopic dipoles are of small magnitude and tend to cancel one another, and hence no measurable potential is produced. This condition is referred to by many authors as *polarization*. When the cell is stimulated, a reorientation of the charge occurs and the cell is said to be electrically active or *depolarizing*. It is during this hypothetical process that the heart produces the P and QRS waves of the EKG. The T wave is considered as produced by the process of repolarization.

Wave Characteristics

In analysis of electrocardiograms, four areas of information are investigated: (1) wave characteristics, (2) time intervals, (3) cardiac potentials, and (4) detailed or average data on the axes of electrical activity. Electrocardiograms are usually considered to be made up of three or more complexes: the P complex, the QRS complex (Q, R and S waves), and the T complex. These five waves or three complexes indirectly mirror electrical changes developing in the heart.

P-wave: The P-wave represents spread of electrical activity through the atrial musculature after the sino-atrial node discharges. In man the P-wave begins about 0.02 second before the atrial contraction. Variations in direction of migration of the electrical disturbance may produce variations in configuration of the P-wave. One of the practical problems in electrocardiology is identification of the P-waves. Identification may be difficult when the P-wave is *iso-electric,* or when rapid heart rates cause the P-wave to be superimposed on the T-wave.

QRS Complex: The QRS complex is produced by an electrical disturbance spreading through the ventricle. It is measured from the beginning of the Q wave or the R wave (if no Q) to end of the last R or S wave.

Duration of the complex should be measured in the lead in which it is greatest, in order to minimize any errors due to iso-electric recordings of the QRS complex at its beginning or termination. First downward deflection is labeled Q, first upward R, while the second downward deflection is labeled S. In the absence of an R deflection the QRS complex would be represented by a single downward deflection; here the descending limb is labeled Q, the ascending limb S, and the wave QS. Additional deflections are sometimes found in the QRS complex and are designated by primes as R′, R″, or S′ and S″.

T-Wave: Passage of the QRS disturbance through the ventricle is presumed to leave the ventricle in a disturbed state both electrically and metabolically. Reconstitution of the resting electrical state of ventricles develops while the ventricular muscle is still contracting and the dipoles developed during the electrical resconstitution or recovery in the ventricle give rise to the T-wave. A negative wave is sometimes seen following the P-wave and represents the recovery disturbance or the T-wave of the atrium. The atrial recovery disturbance is labeled Ta. Ordinarily Ta is buried in the QRS complex and escapes identification. Because T and Ta waves represent electrical reconstitution of cardiac musculature, any factor which might alter physicochemical processes in the heart may alter the T and Ta waves.

Cardiac Intervals

Cardiac time periods usually studied are the P-P, R-R, and P-R intervals, the QRS duration, and the Q-T and the T-Q intervals.

P-P and R-R Intervals: The P-P interval gives the period between atrial contractions and is measured from beginning of one P wave to beginning of the next P wave. From the relationship *Frequency of contraction* = (*Unit of time*) / (*Period of contraction*), atrial frequencies or rates may be calculated.

R-R interval gives the period between ventricular contractions and is measured from the peak of one of the QRS waves to the peak of the same wave in the next cycle or heart beat. The R-R interval allows calculation of ventricular rates. When adequate measurements of both P-P and R-R intervals are obtainable, they are usually identical in normal animals. The P-wave, as noted above, is frequently difficult to identify and hence reliance is usually placed on the R-R interval when one wishes to determine heart rate. The P-P and R-R intervals under some physiological conditions and under many pathological conditions are not identical and hence atrial and ventricular rates are not necessarily the same.

P-R Interval: P-R interval extends from the beginning of the P-wave to the beginning of the QRS complex. The P-R interval is a measure of the time required for the electrical disturbance to traverse the atrial musculature plus the transmission time into the atrioventricular node. The P-R interval thus measures impulse conduction time from the sino-atrial node to the ventricle.

QRS Duration: QRS complex is measured from its beginning at the Q or R wave to its end on the R or S wave, in the lead with the greatest length to avoid errors due to iso-electric portions. Number and type of waves in the QRS complex depends upon the orientation of the lead axis with respect to the axis of the QRS complex; thus the component waves are not usually measured separately.

Q-T Interval: Q-T interval represents the time from the beginning of the QRS-complex to the end of the T-wave. It is equivalent to total duration of ventricular electrical changes within a beat and is essentially coincident with the period of excitation and contraction of the ventricle. Thus the QT interval is referred to as *electrical systole* (35).

T-Q Interval: T-Q interval, from the end of the T-wave to the beginning of the QRS complex, is essentially coincident with the period of ventricular relaxation and has been referred to as the period of *electrical diastole* (Spörri). Obviously, when ventricular rate is not varying, the RR interval equals the sum of the QT and TQ intervals. Frequently variation in PR intervals and the interval represented by the segment between end of the T-wave and beginning of the P-wave (TP segment) leads to a lack of equality between the RR interval and the sum of TQ and QT intervals.

Cardiac Potentials and Cardiac Electrical Axes

Normally *electrical potentials* are developed at three different periods in the cardiac cycle. Potentials give rise to proportional galvanometer deflections which are recorded photographically. At any given time the galvanometer deflects a maximum when the leads are parallel to the momentary resultant dipole. Deflection in leads not parallel to the resultant dipole (but with equivalent distances of electrodes from the heart) is given by product of the maximum deflection and cosine of the angle between the dipole and the leads (See Figures 5B and 6D). By proper orientation of the leads, the galvanometer deflections may be used to measure magnitude and direction of electrical potentials generated by the heart (17). *Direction* of the lead for maximum potential at a given moment is spoken of as *axis* or direction of the cardiac potential at that moment.

For a given momentary dipole equipotential surfaces can be outlined around the heart. Equipotential surfaces intersect body surface in equipotential lines (15). If both electrodes of a bipolar lead are placed on an equipotential line the potential difference or RI drop recorded will be zero. If electrodes are on lines of different potentials, a potential difference will be obtained and a galvanometer deflection can be recorded.

Cardiac Axes: For P, QRS or T complexes the resultant dipole varies from moment to moment. If one is interested in momentary effects, changing directional pathway of the dipole and its changing magnitude are followed and plotted on a polar coordinate system in three dimensional space. Since the potential generally comes back to a null or zero level between each wave, the path repeatedly reverts to the origin and a loop is formed for each wave of the cardiac cycle. The pathway described gives rise to loops repeated with each heart beat. As any point on the loop designates a direction and a magnitude, the pathway is called a *vector loop*.

If one is interested in average effect of a complex, a band of zero potential (expressing absence of any net directional activity over the duration of the complex) may be found on the body surface for each of the three complexes. The line or band of zero potential is located by exploring with a Wilson unipolar lead for areas yielding no net deflection of the galvanometer during the complex under investigation. All unipolar leads from this band will exhibit no net deflection of the galvanometer over duration of the complex. This band is called the null or transitional pathway for the complex. In general a plane may be passed through this band, and this plane is perpendicular to the net direction of the momentary dipoles. Net direction of dipoles for a given complex, expressed in a three dimensional system of coordinates (usually polar: ρ, θ and ϕ), is referred to as the *cardiac electrical axis* for the complex.

One method of establishing net direction of the axis for a given complex is to determine the lead of greatest potential. Another method is to seek two other bipolar leads, at angles to one another, such that the net potential in each is zero. Axes of both these leads are perpendicular to the net dipole, and their plane is also perpendicular to the dipole. Direction of the dipole is then defined as perpendicular to the plane determined by two isoelectric leads. A third method is to obtain the band of zero potential with the Wilson unipolar electrode, and the dipole direction is then defined as the perpendicular to the plane of the band of zero potential.

These theoretically simple methods are difficult, time-consuming and tedious to apply because each animal varies greatly so that extensive exploration of the electrical potentials is required. In practice a fourth method is followed. Here a set of standard anatomical electrode positions is set up to yield ease of application of electrodes and minimum artefacts in the recording. Dipole direction is then determined geometrically by constructing the resultant dipole from cosine components available in at least two planes (as the dipole has both direction and magnitude it is a vector quantity as opposed to a scalar quantity which has magnitude only). Details will be given later under methods.

Einthoven Triangle: When Einthoven (14) introduced his sensitive string galvanometer to record cardiac potentials, the right hand, left hand, and left foot were placed in a saline solution in metal buckets as electrodes. Roughly it could be considered that the heart was in the center of an equilateral triangle formed with the right shoulder, left shoulder, and pelvis as apices, and that potentials were being recorded across these points. Thus electrodes in the initial Einthoven system were considered as roughly equidistant from the heart, and roughly equidistant from each other, and the line joining the electrodes of a given lead were roughly at 60 degree angles with the lines joining the electrodes in either of the remaining leads. If lines are drawn through the centrally placed heart parallel to the sides of the equilateral triangle a bipolar triaxial system is developed, with the axes forming a system of 60 degree angles (See Figure 5A: leads S-I, S-II, and S-III).

Goldberger Triaxial System and Hexaxial System: In the Goldberger (16) system two of the electrodes are joined to a common terminal. In each of the three Goldberger unipolar voltage leads (See Figure 5A: leads aVR, aVL, and aVF), one connection can be considered as concentrated at the electrical mid-point between the electrodes joined to a common terminal. The other connection can be considered on a line perpendicular to the line joining electrodes with the common terminal. Thus for lead aVF in man one has essentially placed a shunt across the right and the left forelimb and the unipolar electrode is placed on the left rear limb, which again can be considered as the pelvic area. Axis for this lead runs parallel to the long axis of the trunk from the shoulder region to the pelvis and is perpendicular to the line joining the right and left forelimb electrodes.

Thus the Goldberger shunt (and also the central terminal of Wilson) tends to orient the lead axis through the electrical center of the heart; and the axes of each of the unipolar limb leads (aVR, aVL, and aVF) are along lines from the positive unipolar electrode through the center of the heart.

The Goldberger leads have axes perpendicular to sides of the Einthoven triangle, and axes of the three Goldberger unipolar leads are at right angles to axes of the Einthoven bipolar leads (Figure 5A). As the unipolar electrodes are in the same position as those used for the bipolar limb leads, they will give rise to axes 60 degrees apart through the center of the heart. This Goldberger triaxial system of unipolar leads is similar to but oriented 30 degrees from the Einthoven bipolar triaxial system.

Further modification by Pallares (Dimond; 13) superimposed the bipolar triaxial system on to the unipolar triaxial system to produce a hexaxial system in which all lead axes (I, II, III, aVR, aVL, aVF) were oriented like spokes of a wheel, 30 degrees apart (Figure 5A).

Vector Loops: Electrical potential of the heart regularly departs from the resting state and this change is recorded on the moving EKG record. The record is a measure of the component of the momentary resultant potential parallel to the axis of the lead. If two EKG leads are taken simultaneously and coordinated through suitable electronic equipment, a loop can be seen written on an oscilloscope screen. This loop can be considered as reflecting the resultant electron displacement caused by reacting cardiac tissue. Such a loop can also be constructed from two or more EKG tracings (24). When spatial loops are constructed, the QRS and T deflections obtained with any lead can be predicted down to minute details (17, 16).

One is frequently concerned with net electrical effects in a given complex rather than in momentary details. Net electrical effect is expressed simply as a resultant vector by measuring and algebraically summing postive and negative areas of a complex on the electrocardiogram. In practice the amplitude of the wave complex is used to approximate the area. This method usually provides a good approximation for the resultant vector. In cases where approximation appears to be faulty, the vector loop must be constructed.

This discussion of wave forms, electrical potentials, and cardiac axes has been presented in simplified and general terms. A more rigid discussion with reference to beef cattle electrocardiograms is currently inadvisable. One reason is that animals do not present simple geometrical configurations such as equilateral triangles. A second is that in electrocardiograms one is ultimately concerned with electrical rather than spatial dimensions of animals. The necessary electrical data, such as relative resistances and capacitances, are currently not available. If one could establish a triangle such that the impedances between electrodes placed at the apices were equal, and such that the impedance between the apices and the heart were equal, then it would be worthwhile developing a rigid discussion of electrical properties in cattle. However, even the rough approximation offered here has led to significant developments in human cardiology and should contribute much to the still open field of bovine cardiology.

Literature Review

Many papers have been concerned with establishment of electrocardiographic (EKG) patterns for cattle. All early studies of bovine electrocardiograms were carried out on dairy cattle. Early attempts were directed towards duplicating wave forms of human electrocardiograms, but it soon became apparent that there were fundamental differences between cattle and man. Many papers have been concerned with cardiac intervals (1-3, 5, 6, 10, 19, 22-24, 30-33, 35-42), case histories of abnormalities (10, 20, 22, 30, 37), the diagnosis of disease by use of electrocardiograms (20, 22, 33, 35, 36, 39), and cardiac alterations under experimental conditions. These roughly include the fields of exercise (35), surgery (3) and drug effects (1, 5, 6, 31, 32, 40, 41, 42).

This literature review will consider pertinent papers on the normal form of the electrocardiogram, the QRS-T relationship, and the cardiac axes. Brief summaries will be given of information on cardiac alterations in disease, during exercise, after surgery, and after administration of drugs.

Normal Electrocardiograms in Cattle

Nörr had introduced electrocardiography into veterinary medicine in 1913 and published the first accounts of the electrocardiogram in cattle in 1921 and 1922 (28, 29). Nörr noted that limb leads in cattle gave small potential excursions (See Figure 1, first column). Nörr also noted that leads can be found with greater potential excursions. The maximum QRS potential was recorded from electrodes placed near the heart apex under the left olecranon and on the right side of the neck near the scapula. In studies by Nörr large zinc plates were used as electrodes.

Lautenschlager's (1928) thesis at Giessen, as quoted by Spörri, was concerned with electrocardiograms of dairy cattle. Lautenschlager used needle electrodes inserted subcutaneously (36). Nörr, Lautenschlager and Spörri all recognized that the anatomical cardiac axis of cattle was not parallel to the plane of the leg leads, and felt that a satisfactory electrocardiogram had not been obtained unless the QRS complex was represented by maximum excursions in a bipolar lead. To obtain maximum excursions, Lautenschlager explored each animal and selected needle electrode sites, usually in the heart apex and prescapular areas.

Spörri (35, 37, 40) pointed out that dependence on a single lead often gave rise to difficulties in interpretations of electrocardiograms. To provide an Einthoven triangle, and to eliminate erroneous interpretations of isoelectric segments as indicating a zero potential in the heart, Spörri chose a third electrode position which would be topographically and anatomically easily definable, and which would produce an EKG with good wave form and with good repeatability. The third point was taken at the sacral eminence (den Kreuzbeinhöcker) in the rump area and allowed Spörri to provide counterparts of Einthoven leads II and III.

In the words of Spörri, (35):

> Das Ende der T-Zacke sagt jedoch nicht mit Sicherheit dass nun im Herzen keine elektrischen Spannungsunterschiede mehr bestehen, denn man kann sich leicht vorstellen, dass beide Ableitungsstellen infolge gleicher elektrischer Beeinflussung das gleiche Potential haben, also isoelektrisch sind und somit die Kurve im Ekg sich auf der Nullinie bewegt. Bei Anwendung von drei oder mehr Ableitungsstellen, wie wir es in unseren Bestimmungen taten, dürfte diese Möglichkeit jedoch praktisch ausgeschaltet sein.

Spörri (35) noted that placement of the electrode in the region of the cardiac apex was especially critical. Here only a slight displacement of the electrode often gave curves of quite different appearance. Bergman and Sellers, 1954, used a lead, described as precordial with electrodes near the heart apex and at the right scapula tip, because, in their opinion, this bipolar lead gave standard and duplicable results from animal to animal (6).

Many authors since Lautenschlager, Nörr, and Spörri have commented on the small magnitude of potentials in the limb leads (1, 2, 5, 6, 19, 25, 32). Nörr noticed it was common in cattle EKG records to see fluctuations of the QRS complex which were synchronous with the respiratory cycle. This change in QRS potential from longest to shortest was in a ratio of 11 to 10 (prescapular-apex lead).

P-Wave: Platner, Kibler, and Brody, 1948, included 10 dairy cows and 13 dairy calves in their electrocardiographic study of farm animals (31). In dairy cows the P wave was diphasic in limb lead I and only once was there an inversion in lead III. The P wave was variable in dairy calves, sometimes being diphasic in lead I and sometimes inverted. There was no P inversion in leads II and III.

Manning (25) pointed out that the P wave is isoelectric in leads S-I and S-aVR, and that the P axis is directed ventrally and to the left. Notched P waves are prevalent in leads parallel to the P wave axis. Notched P waves were absent in the series of Alfredson and Sykes (2) and only one notched P wave was noted by Platner and his coworkers (31). Alfredson, Sykes, and Platner used only limb leads. In lead S-I of Manning's study there were no notched P waves.

Heart Rate: Nörr cited Ellinger that the heart frequency ranged from 36 to 60 for bulls and oxen, while cows had rates from 60 to 80 per minute. The range was altered in pregnancy to 78 to 108 beats per minute. For 2 to 60 day old calves the rate was between

110 and 134. Ellinger also observed that mountain breeds had a lower heart rate than the low-lands breed (28).

Muscle Tremor: Nörr noted that a common artefact in the EKG of cattle was the presence of potentials due to muscle tremor. The fact that cattle do not have a locking mechanism to rest their limb muscles, as do horses, accounted, according to Nörr, for the muscle tremor potentials to be found in the EKG records of cattle. Tremor artefacts are not seen in the EKG records from horses (28).

QRS and T Relationship: A very important characteristic difference between human and bovine electrocardiograms is that QRS and T complexes are usually of opposite sign in cattle, while in man they usually have the same sign. This difference in sign can be noted in all published normal bovine electrocardiograms. In 1940 Ralston, Cowsert, Ragsdale, and Turner (32) specifically commented that EKG of cattle was quite different from that of the human in that the T-wave in lead II was inverted in the cow.

The T-waves were classified by Spörri into IV groups. Most (82-93%) of the normal T-waves showed a positive deflection and the remainder a minus-plus complex. A negative or a plus-minus T-wave could often be found in individuals considered not to be normal and healthy. It was emphasized that no normal bovine heart yielded a purely negative T-wave. Lautenschlager was reported to have found even a greater percentage of cattle with a purely positive T-wave (36).

Cardiac Axes: A second difference of importance between man and cattle lies in the direction of the anatomical and the electrical axes of the heart. Nörr (28) noted that in cattle 5/7 of the heart musculature is situated left of the median plane, and the anatomical axis of the heart is even more vertical than in the horse, the species first studied by Nörr.

Since limb leads in cattle were not at all comparable to those of man, either with respect to the anatomical axis of the heart or with respect to the EKG obtained, Nörr sought another lead. In order to obtain what Nörr considered a typical QRS complex, it was necessary to place electrodes in the prolongation of the longitudinal axis of the heart. The bovine heart is almost vertical in the thoracic cavity, and its theoretical axis runs from the vicinity of the cervical scapular angle in the *regio prescapularis* to the *regio apicis*. Because waves obtained by this lead were still different from those of man, Nörr proposed adoption of the Kraus-Nicolai nomenclature, which had been developed for the horse. This proposal has not been adopted by subsequent electrocardiologists. While Nörr (28) and Spörri (35) were concerned with the lead giving the greatest excursion in the

QRS complex, they did not specifically distinguish between the anatomical axis of the beef heart and the electrical axis.

However, Nörr pointed out that Sachs found in man, during and after pregnancy, significant differences in magnitude of the QRS and T complexes. These changes were attributed to the altered heart position in pregnancy. In cattle, on the contrary, Nörr found no change of the EKG potentials due to pregnancy. This Nörr attributed to the facts that in cattle a change of heart position does not occur with pregnancy because the ruminant stomach lies as a buffer between foetus and diaphragm, and that in cattle the heart has a different position or relation to the diaphragm than in man. Thus Nörr recognized some relationship between the anatomical axis of the heart and the EKG potentials recorded.

Agduhr and Stenström, 1930, using limb leads, pointed out that it was difficult to keep electrode contact resistances constant, and thought that changes in magnitude of the QRS potentials might in part be experimental artefacts, and that construction of cardiac axes was less reliable for cattle than for man (1). Agduhr and Stenström, in case history reports, sometimes commented that the QRS axis often changed with age and/or with administration of cod-liver oil.

Barnes, Davis, and McCay (1938) (5) used limb leads in their study of cod-liver oil toxicities because they thought time intervals could be adequately measured. Since they recognized the heart of the calf did not lie in the plane of the limb leads, they made no attempt at a complete analysis of their electrocardiograms.

Alfredson and Sykes (2) were the first to give extensive statements on direction of the cardiac axis in a study of 97 dairy animals. Leg leads were chosen despite the fact that their position relative to the long axis of the bovine heart were considerably different from man. Use of limb leads required a change in the procedure used by human electrocardiologists in measurements of intervals. Readable complexes were always selected for measurement of intervals, rather than selecting a given lead for determination of interval lengths because of the extreme range of position of the QRS axis in cattle. For uniformity and since the longest interval in any lead of the first monthly tracing was rarely exceeded in subsequent records, the *greatest interval* in *any lead* of the first tracing was arbitrarily selected for tabulation.

Using the limb leads, Alfredson and Sykes noted that the QRS axis was in the range $+30°$ to $+90°$ for 50% of the animals. The axis in 17% was in the $+91°$ to $+170°$ range. Only 17% were in the $-30°$ to $-170°$ range, while 6% showed the extreme deviation of 180°. No values were found between $+30°$ and $-30°$.

Electrocardiograms of nine animals were such that it was impossible to determine the electrical axis even approximately. These electrocardiograms were generally characterized by unfavorable QRS complexes (diphasic and vibratory) of small potential. It must be noted that Alfredson and Sykes were concerned with the QRS axis in the plane of the limb leads, a plane which is almost perpendicular to the anatomical axis of the heart and to the axis of the lead, described by Nörr, Lautenschlager, and Spörri, giving maximum QRS potential.

From a study of limb leads, Agduhr and Stenström came to the conclusions that in the young calves the QRS electrical axis of the heart has a direction which in man would indicate left ventricular preponderence, and that during early postnatal growth direction turns from left to right. In healthy calves, after a few weeks of life, the time intervals become very stable although the animals are doubling or quadrupling their weight. Hence, as the heart is also growing, there must be a considerable increase of the rate of conduction and of the mass of heart muscle.

Materials and Methods

Electrocardiographic records were taken from three closed lines of Hereford calves maintained at the Oregon Agricultural Experiment Station in Corvallis, Oregon. The Lionheart cattle line has been closed to outside breeding since 1950. The Prince and David lines have a common origin separate from Lionheart. No outside bulls have been used for breeding in the Prince line since 1948, and in the David line since 1950. Before 1950 some cows were interchanged between the Prince and David lines, but since 1950 these two lines have been maintained separately.

The main body of data for this manuscript comes from 35 Hereford calves (E series) born in 1955. Electrocardiograms are very complex and interpretation requires an extensive introduction. Study of electrocardiograms at Oregon State College was initiated in March, 1955, and the process has undergone considerable developmental alteration to date. For this reason, animal F-25 of the 1956 calves was used to obtain electrocardiograms with a variety of leads to provide a consistent background in discussing interpretation and analysis of bovine electrocardiograms (Figures 1, 2, 3). Analysis and data from calf F-25 form the greater and introductory part of the bulletin. Data from the 35 E calves are presented and discussed with reference to potentials and to direction of the cardiac axis of the QRS complex.

Figure 1. Leg, leg-thoracic, leg-scapular, and cross-sectional leads.

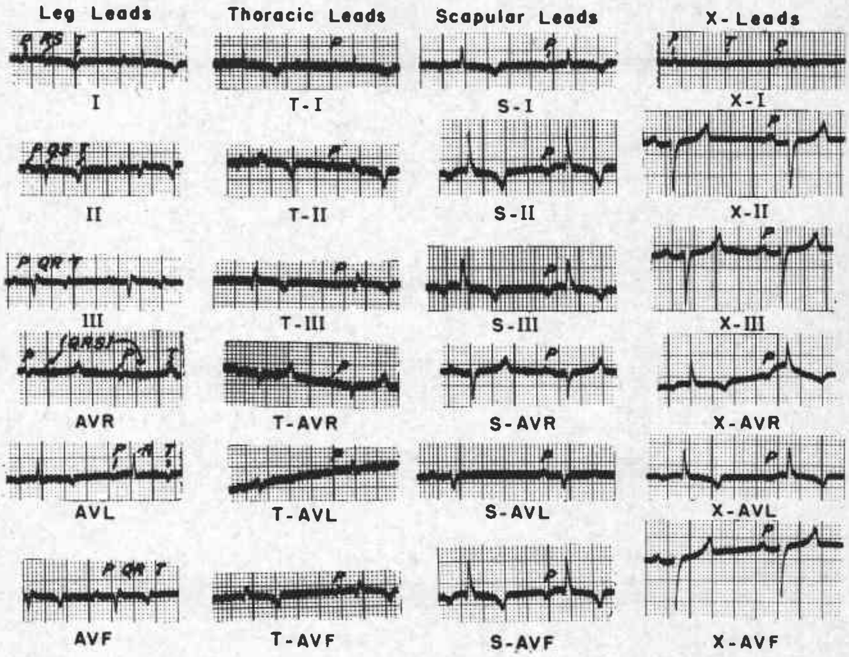
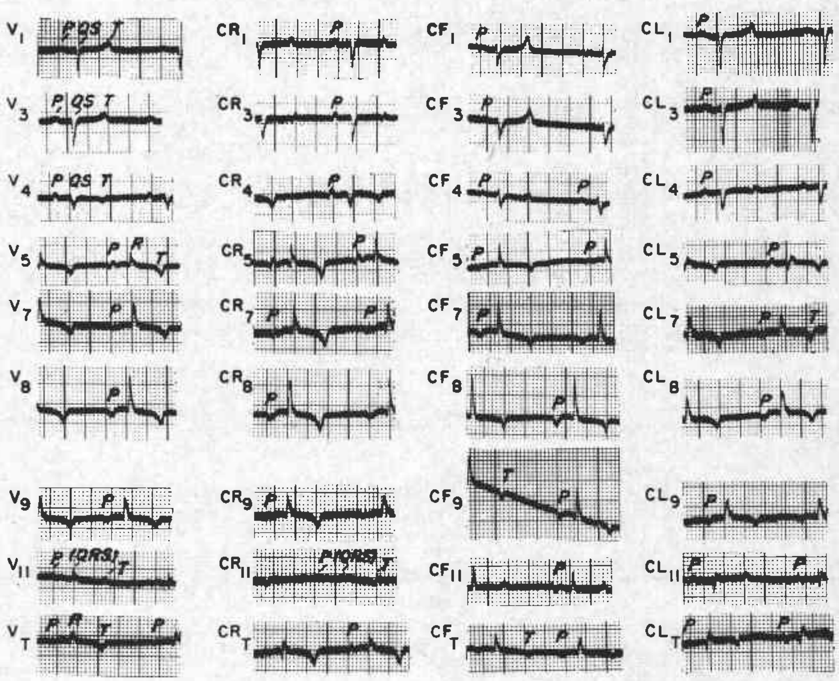


Figure 2. Chest-leads with leg-leads.



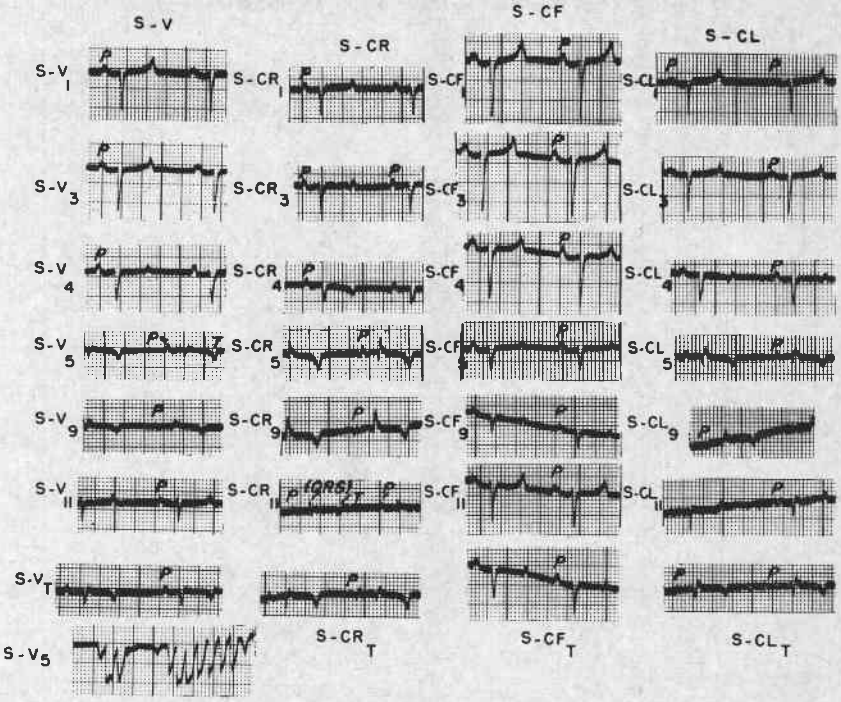


Figure 3. Chest-leads with S-leads.

Management of Calves

Calves used for this study were born in spring, 1955, and were weaned at about 425 pounds body weight. After weaning, they were grouped by sexes into pens of six animals. From first feed period until attaining a weight of 800 pounds, the calves were tied by neck chains at individual feeding stalls twice a day. Feeding periods of approximately three to five hours twice daily were maintained as uniformly as possible. Calves had access to automatic water fountains at all times. The animals were weighed once weekly. The management procedures used and recommended by Dahmen and Bogart (12) were followed and calves were fed a completely pelleted ration composed of two parts chopped alfalfa and one part concentrate. The ration is described in more detail by Nelms, Williams, and Bogart (27).

After weaning, the calves were kept in test pens and were subjected to daily handling. Since the electrocardiograms were taken in the barn itself, the animals were generally amenable to, but untrained for, the procedure required. Each subject was led from test pen to recording area, and hair was clipped where necessary from the body surface for electrode and microphone placement. The calf subsequently was left standing and unrestrained except for a rope halter tied to a post. Occasionally struggling was severe and prolonged delays ensued until the calves became somewhat quiet. Rubber mats had been arranged to provide insulation from the ground and to minimize artefacts due to 60 cycle alternating current. Instruments were protected from calves by interposing bales of hay.

Thirty-five Hereford calves born in 1955 (the E series) were investigated electrocardiographically at body weights as close to 500 pounds and 800 pounds as possible. Routine of performance testing included weighing each animal weekly, and this allowed rather precise determination of dates at which 500 and 800 pounds weights were attained. Earliest records at 500 pounds weight were taken in mid-September, 1955, and the last in mid-April, 1956. At 800 pounds weight the first was taken in January, 1956, and the last in September, 1956.

Equipment

Instrument used was a twin-beam cardiette with a two channel photographic research recorder. It was equipped with a general purpose amplifier for recording electrocardiograms and a phonoamplifier for recording heart sounds. The general purpose amplifier and phonoamplifier had separate control panels. On the control panel for the general purpose amplifier was a switch allowing automatic selection, for standardization, lead I, II, III aVR, aVL, aVF, V, CR, CF, or CL from five electrodes individually connected to the five strands of the five wire patient cable.

The phonoamplifier had a switch allowing two distinct methods for recording heart sounds. With the switch in the position labeled stethoscopic, the sound record obtained gave more prominance to low frequency components than did the human ear. This position records sounds as received by the microphone. In log position, the signal delivered to the galvanometer had low frequency components attenuated, and medium and high pitched heart sounds were registered more efficiently. The log position more nearly reflected heart sounds perceived by the human ear.

Deflections of the galvanometer were recorded on photo paper 3A-9. Paper speeds of 25 mm or 75 mm per second were obtained with a paper speed selector. A mechanical link to the timer provided time lines on the paper at 1.0, 0.2 and 0.04 second.

Accessories accompanying the twin-beam cardiette are microphone, audiophone, microphone bells, perforated rubber straps, electrode paste and electrodes, patient cable, ground wire, and power cord.

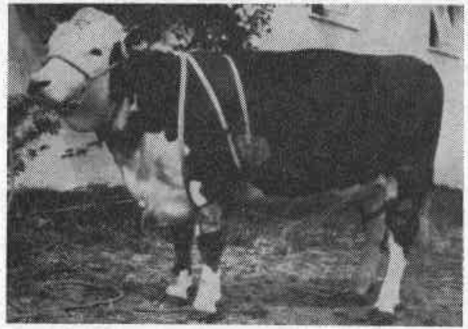
Size of the calves and the need for slack to prevent damage to the equipment when the calves moved necessitated the design of longer connections to electrodes, microphone, and audiophone. A five-wire cable with a main cable 12 feet and separate leads 6 feet long was designed for connection to the electrodes. Extensions 10 feet long were ordered and obtained for the microphone and audiophone cable. (Two audiophones were required for coordination of activities between an instrument man and the animal handler. The audiophone wire extension was needed to enable the operator by the animal to listen to the microphone during adjustment.)

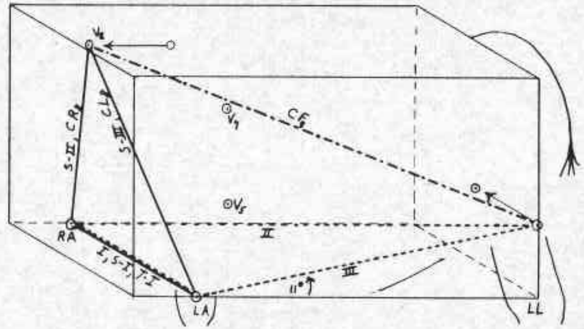
Full insulation of the animal from its surroundings was also required to prevent grounding and a resultant 60 cycle artefact. Rubber mats about 36 x 36 x 1/16 or 1/8 inches were acquired for this purpose. In the dairy barn, every pipe and stanchion in the stall that the animal could touch, as well as the floor, had to be covered with insulating material. In the beef barn only floor mats were needed as the halter was secured to a wooden post, while bales of hay beside the animal tended to restrict motion, protect the equipment and served as a convenient table. At first many spare mats were required in order to effect changes whenever an animal urinated, but later tar paper (originally discarded in favor of the mats because tar paper alone scared the animals when they walked on it) was placed on the ground under the mats and sawdust applied to absorb the urine before an electrical ground was effected.

Procedure for Taking Electrocardiograms

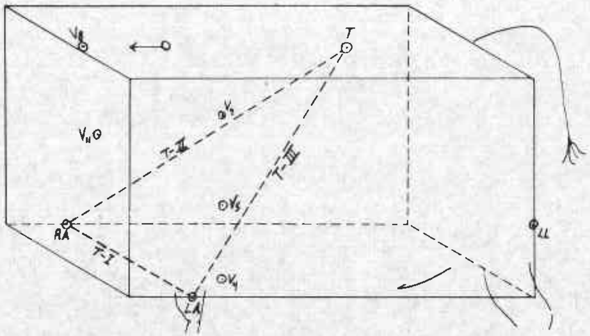
Before taking electrocardiograms, hair had to be clipped from sites selected for electrode and microphone placement. Hair interferes with the microphone both by reducing amplitude of desired sounds and by inducing hair friction sounds of high frequency. Hair also interferes with a close contact of electrodes with skin. Site for the microphone and sites for electrode placement were freed from long hair by an electric sheep clipper. The sites for the electrodes were then cut more closely by means of electric human hair clippers. In the absence of dirt and heavy guard hairs, only the hair clippers were used, especially in younger calves. (Use of the limb leads is not without danger to the operator. The operator must be alert and not allow his attention to be diverted while barbering the animal or when attaching the electrodes.) Electrode paste was carefully worked into the skin at sites of electrode placement, and the electrodes were secured in place by standard perforated rubber straps.

Two chest straps around the animal served to secure the prescapular electrode with one strap in front of one forelimb and behind the other forelimb. The second strap was placed behind the first fore-

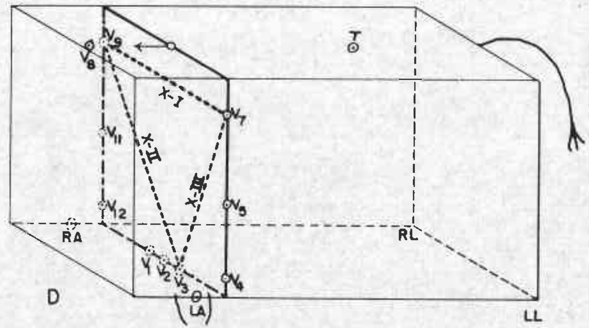




B LEG (L-) LEADS, SCAPULAR (S-) LEADS, AND THE SEMI-SAGITTAL LEAD COMPLEX



C THORACIC (T-) LEADS



D CHEST LEAD POSITIONS AND THE CROSS-SECTIONAL (X-) LEADS

Figure 4. Electrode positions, Einthoven triangles, and projection planes.

limb and in front of the second forelimb so that the straps intersected in the prescapular position (Figure 4A).

A chest strap behind the olecranon provided security for the chest lead electrodes and microphone. The lumbar electrode cannot be secured because a strap on the abdomen disturbs the calf. Usually the lumbar electrode will remain in position for the few seconds required for records.

Microphone position was determined after many possible sites had been explored. The best sound pickup is just under the olecranon on the left side, and this site is easily available with a stethoscope. However, the EKG microphone is large and bulky and will work under the olecranon only when the animal has his left leg stepped ahead of the normal position. Since this is difficult to achieve, the sternal hollow was used routinely for sound pickup, and this location gave satisfactory sound reproduction except on larger animals. Furthermore, the microphone could be secured in the sternal hollow by chest straps. The microphone can be made more secure if two straps are affixed to holding lugs on the microphone.

Electrode Connections: Initially five or more electrodes were placed in position. Five electrodes were connected to the patient cable whose terminals distal from the cardiette were marked RA, LA, LL, RL, and C respectively for right arm, left arm, left leg, right leg, and chest. The RL terminal is always connected to a ground on the cardiette, and the cardiette itself is suitably grounded.

RA, LA, LL, and C terminals of the patient cable were first connected to electrodes at sites corresponding to the labels. Proper paper speed was chosen and lead selection switch set at standardization. Sensitivity was adjusted so that a potential difference of one millivolt would give a deflection of 10 mm. Subsequently, with the paper still moving, leads I, II, III, aVR, aVF, aVL, V, CR, CF and CL were dialed in rotation. Each position was held for about five seconds unless a longer record was desired.

C terminal was subsequently placed in various positions on the chest under the strap around the calf behind the front legs as described under basic concepts (p. 5). After each positioning of the C electrode on the chest, the lead selector was dialed through leads V, CR, CF, and CL only since I, II, III, aVR, aVL, and aVF were not changed by moving C.

Electrode terminals RA, LA, LL, and C were then moved as required to other positions described under basic concepts (p. 6-7) and electrocardiograms obtained for the T, S, and X series of leads.

The research cardiette uses a light beam instead of a mechanical arm, and must be recorded on photographic paper. The photographic paper comes in rolls 100 feet long by 6 cm wide of which a receiving tank will take only 50 feet. Lengths of record beyond 50 feet jam the receiver and cause loss of information. Suitable lengths of record were taken and were developed in 11 x 14 inch print trays with X-ray developer or D-72 to which 80 grams of borax were added per gallon. The record was subsequently treated with fixing solution, washed, and dried.

Analysis of Electrocardiograms

Cardiac intervals are obtained by direct linear measurements to the nearest 0.01 second along the time axis (abscissa), and potentials recorded are obtained to the nearest 0.05 millivolts by direct linear measurement along the ordinates. Magnitude and direction of the QRS axis potential is obtained in several steps: First, magnitude and direction of the component recordable in a given plane A is computed. Secondly, direction and magnitude of the component in another plane B, preferably at right angles to plane A, is also computed. Properly expressed these two computations define magnitude and direction of the QRS axis potential.

Geometrical Construction of Cardiac Axis: Computation of the component recordable in a given plane is based on the hexaxial system (13, p 43-58) of leads discussed under basic concepts. Maximum QRS potentials above and below the isoelectric portion (TP segment from end of the T to beginning of the P complex) are measured and algebraically summed in each lead of a hexaxial system. Potential above isoelectric level is positive and potential below the isoelectric level is negative. Respective algebraic voltages recorded are plotted on leads I, II, and III of the hexaxial system (Figure 5A) with *one unit of length equal to one-tenth millivolt.* Potentials in the Goldberger leads are multiplied by 1.15 and the respective products plotted on the aVR, aVL, and aVF leads. At this point the figure resembles six spokes of a 12-spoke wheel, with spokes of uneven length and unevenly spaced (Figure 5A).

If perpendiculars are now drawn to the spokes or axes at points corresponding to respective voltages recorded, the perpendiculars tend to intersect at a point, but may intersect over a small area (Figure 5B). Failure to intersect at a point usually is due to muscular movements, including respiratory cycles, which prevent QRS complexes from being identical. Error in mesaurements or inadequacies in the simple electrocardiographic theory previously summarized may also be responsible for failures of the six perpendiculars to intersect at a point.

The line drawn from the origin to the point of intersection of the perpendiculars (Figure 5B and 5C) gives direction and magnitude of the maximum component of the QRS axis recordable in the

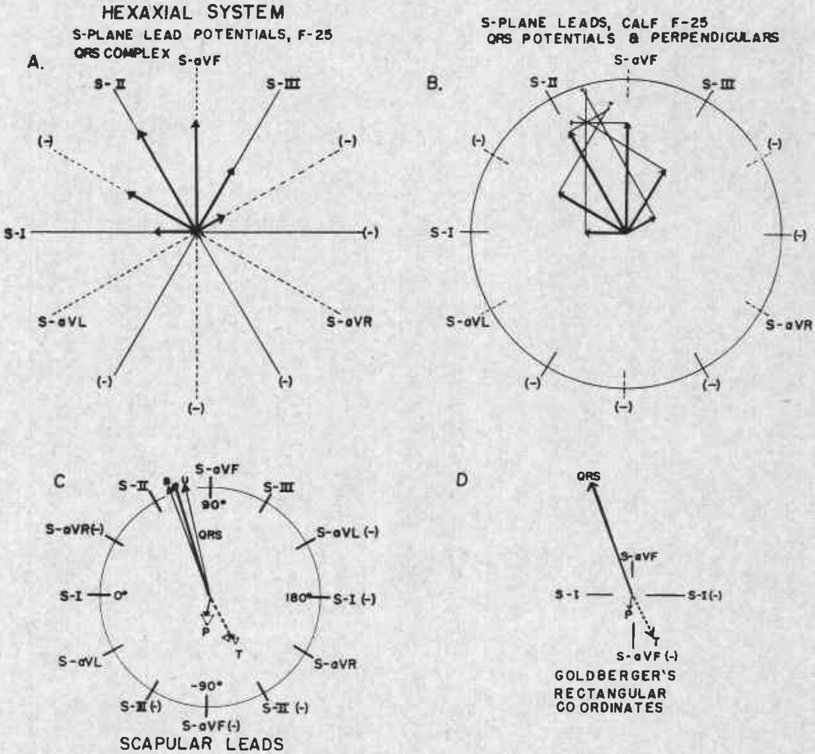


Figure 5. Vector determination.

chosen plane. If a unique point of intersection is not obtained, a choice is made between the point where most perpendiculars intersect and the central point in the area of intersection. (The area of intersection of the perpendiculars is rarely so diffuse that an average position of the axis is meaningless. Here a vector loop may be constructed to allow more satisfactory study.) In the survey of the E calves considered in this bulletin, only three bipolar leads (or a triaxial system) have been measured and used to calculate the direction of the axis projection in a plane.

Expression of Axes in Rectangular Coordinates: The component of the axis in the chosen plane A can be expressed in several notations of which the two most common are rectangular coordinates and spherical coordinates. In the rectangular coordinate system, position of the point of the vector would be given by $a\mathbf{i} + c\mathbf{k}$, where $\mathbf{i}$ is a unit vector along the x-axis and $\mathbf{k}$ is a unit vector along the z-axis of the chosen plane.

The unit vectors **i** and **k** are used at this point since the **xz** plane has been taken through the leg leads, with the positive direction of **x** from head to tail. Thus caudad from the heart is positive, and cephalad from the heart is negative. The symbol **ai** represents a vector of length a along the x-axis; the sign of a may be positive or negative. The positive direction of z is taken to the left of the calf, and the negative direction to the right of the calf. The symbol **ck** represents a vector of length c along the z-axis; c may be positive or negative.

Magnitude and direction of the component of the QRS axis recordable in plane B is obtained in the same manner as for plane A. If plane B is perpendicular to plane A through the O-Z axis, then components in plane B can be expressed in rectangular coordinates as $b\mathbf{j} + d\mathbf{k}$. In general, coefficients of **k** in plane A and in plane B should be equal, but may vary from equality because of animal movement or errors inherent in method and theory. If plane B is perpendicular to plane A but does not include the x or the z axes of plane A, the j component could still be obtained by suitable calculation.

Plane B has been chosen as the cross-sectional plane through the prescapular space, the right forelimb insertion, and the left forelimb insertion (S-plane). This plane is perpendicular to the plane of the limb leads. The positive direction of the y axis is taken from the ventral to the dorsal aspect of the calf. Thus dorsad from the heart is positive, **bj** represents a vector along the y axis of length b, and the sign of b may be positive or negative. (It should be noted that this cross-sectional plane and its y axis do not coincide with a vertical cross-sectional plane or the vertical axis.)

Expression of Axes in Spherical Coordinates: When the information from planes A and B is combined, the radius vector is given by

$$\mathbf{V} = a\,\mathbf{i} + b\,\mathbf{j} + c\,\mathbf{k}. \qquad \text{(Equation 1)}$$

The radius vector may be expressed as having a length given by $\sqrt{a^2 + b^2 + c^2}$ and having a position θ degrees from the O-Z axis, and ϕ degrees from the x-z plane.

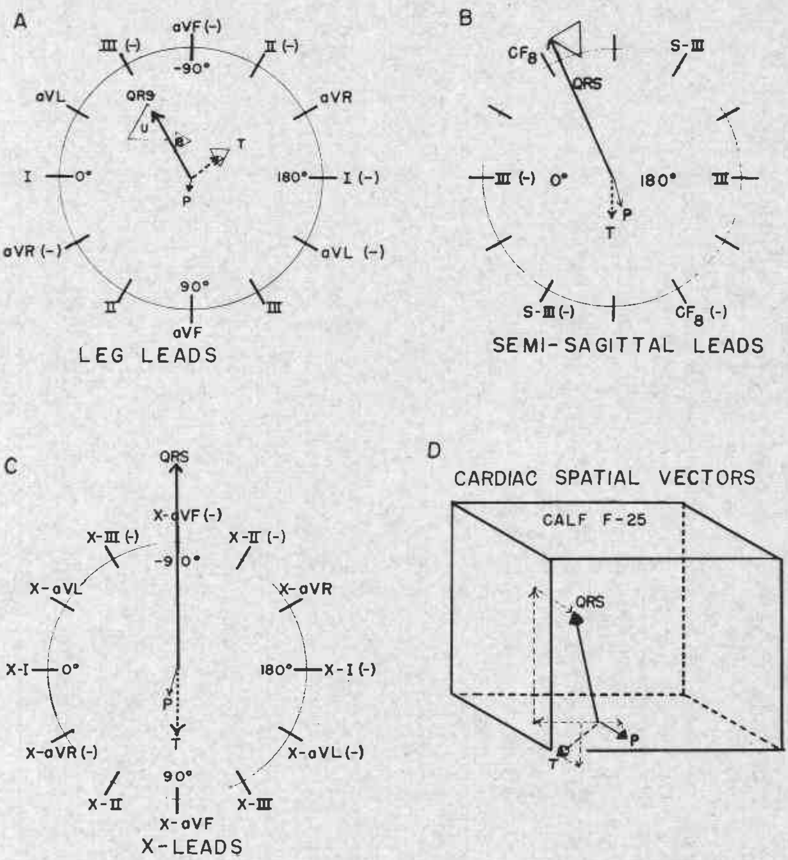
Projection of the vector onto the plane of the limb leads may be expressed as a distance from the origin and the angle θ between the projection and the z axis (Figure 6A). If the projection points along the z axis (coincident with Lead I) to the left, the angle is taken as zero. If the projection has a component along the x axis toward the the cephalic aspect of the calf the angle θ is negative. θ is positive if the projection points caudad. If the projection on the leg lead plane points forward or cephalad along the x axis (lead aVF), θ is -90°; and θ varies in magnitude from 0° to 90° if pointing to the left, and from 90° to 180° if pointing to the right.

The angle ϕ between the vector and its projection on the x-z plane is taken as positive if the vector points dorsad and negative if the vector points ventrad.

Thus the plane of the limb leads establishes an angle θ in a great circle and θ may be interpreted as longitude. The S plane provides data for an angle ϕ which may be interpreted as latitude. The angles θ and ϕ may also be pictured as azimuth and elevation angles.

The angle θ can be read from construction in the plane of the limb lead or can be obtained from the relation that cos θ equals c/p (the component c along the z axis over the projection p of the vector on the leg lead plane).

Figure 6. Cardiac axes.



The angle ϕ may be obtained from the general formula for the angle between two lines (26). The angle ϕ may also be calculated from the relationship

$$\cos \phi = \sqrt{x^2_1 + z^2_1} \;/\; \sqrt{x^2_1 + y^2_1 + z^2_1} \quad \text{(Equation 2)}$$
$$= p/r$$

where p is the length of the projection in the L plane and r is the length of the vector in three dimensional space.

Choice of Planes: Choice of planes to be studied depends on experience, anatomical considerations, and geometrical configurations. It is easiest in three dimensions to work with three planes at right angles to one another. As three planes essentially at right angles to one another we have envisioned the *M plane*, the *L plane*, and the *S plane*. Mid-sagittal or M plane is placed through the interscapular space, the dorsal lumbo-sacral border, and the mid region of the sternum. L plane (Figure 4B) is placed through the insertions of the right forelimb, left forelimb, and left rear limb. S plane is placed through the dorsal prescapular region, and right and left forelimb insertions (See Figure 4B).

These planes are at right angles with one another. The M plane is a vertical plane giving a medial longitudinal and vertical section of the calf. This plane was chosen as equivalent to the xy plane, since the calf was normally viewed from the left side during the taking of electrocardiograms, and it became natural to refer the electrical phenomena to this plane.

Limb leads were chosen partly on analogy with the important limb lead plane in man, and partly because experience indicated that the limb leads, although yielding electrocardiographic complexes difficult to interpret and analyze by themselves, provided valuable information in determining the QRS axis. Limb lead plane is not horizontal with the ground because the hind limbs are attached to the body higher than are forelimbs.

S-lead plane was chosen because it contains a major component of the QRS vector in 500-800 pound calves, yields electrocardiographic complexes relatively easy to analyze and interpret, and is perpendicular to the plane of the limb leads. The inclination of the limb lead plane from horizontal is about 12°. Because the S-lead plane is approximately at right angles to the limb lead plane at the front limbs, the S-lead plane departs from the vertical about 12°.

The vector angle notations in this bulletin are referred to L, S, and M (Mid-sagittal) planes and not to the absolutely horizontal plane or to the transverse vertical plane. This was done since individual variation would require separate correction factors for each animal in order to effect conversion to the comparable geometrical horizontal and vertical planes.

It was also found useful to study a fourth plane, the *semisagittal plane* (Figure 4B) through the prescapular space, the left forelimb insertion, and the left hind limb insertion. As this plane is canted, it has tentatively been termed semisagittal. Specific recordings were not made for this plane, but it was constructed from leads III (left forelimb, left hind limb), leads S-III (left forelimb, prescapular space), and lead CF_8 (prescapular space, left hind limb).

For many 500-800 pound calves the QRS axis lies in or very near the semisagittal plane. Hence maximum potentials are frequently recorded in leads of the semisagittal plane, and a maximum QRS vector component is frequently obtained. Semisagittal plane is used to demonstrate the cephalo-caudal orientation of the vectors and serves as a rough check on the vector orientation computed from the two other planes.

For this bulletin, data on the E calves are presented only for the L, S and SS-planes, and the M plane is used as a visual aid in interpretation when necessary.

Computation of P and T Axes: The magnitude and direction of the axes of the P and T complexes can be obtained by methods similar to those described for the QRS complex. This bulletin is not concerned with P and T axes in the E calves. However, as an example, the P and T axes of calf F-25 at 500 pounds body weight have been calculated and are shown in Figures 5 and 6.

Experimental Findings

The experimental findings will be outlined first with reference to example animal F-25, and then data on the QRS complexes from the E calves will be presented and discussed. In Figures 1 to 3 are given several series of electrocardiograms from calf F-25. These will be examined with respect to QRS, T and P complexes. Subsequently axes will be constructed for QRS, T and P complexes of F-25. QRS is considered first because it has received greatest prominence in the literature. T complex is considered next because both QRS and T complexes have a ventricular origin. This leaves discussion of P complex to last even though first in the sequence of the heart.

Electrocardiograms from F-25

Figure 1 gives electrocardiograms from the six leads of the Pallares hexaxial system for the L, T, S, and X planes. Leads are I, II, III, aVR, aVL, and aVF from above downward and the L, T, S, and X planes are represented in order from left to right.

Figure 2 gives a series of chest leads. Column 1 gives a series of the Wilson unipolar or V leads, with the unipolar lead (pooled electrodes at right forelimb, left forelimb, and left hind limb) shifted through the indicated chest positions. The second column gives a series of bipolar electrocardiograms with the negative electrode on the right forelimb and the positive electrode shifted through the indicated chest positions. The third and fourth columns give electrocardiograms when the negative electrode was placed respectively on the left hind limb and on the left forelimb, while the positive electrode was shifted through the indicated chest positions.

Figure 3 gives electrocardiograms obtained when the electrode marked LL (left hind limb) was shifted to the interscapular position. The first column gives an examination of chest positions with Wilson unipolar leads (pooled electrodes on forelimbs and interscapular space). The second, third, and fourth columns give bipolar electrocardiograms obtained with the negative electrode placed respectively on the right forelimb, the interscapular space, and the left forelimb respectively, while the positive electrode was shifted through the chest positions. An additional figure for SV_5 is given in the lower left hand corner to indicate an electrocardiographic artefact developing when the *panniculus carnosus* is used to dislodge flies.

QRS Complex: L, T, S, and X Planes. Inspection of column 1 of Figure 1 shows that the QRS complex has the smallest potential in the aVR lead, the largest positive magnitude in aVL, and the largest negative magnitude in either aVF or III. If one orders the leads from greatest negative through zero to the greatest positive magnitude, one obtains aVF, III, II, **aVR,** I, aVL. In Column 2 or the T plane, the order of QRS from negative to positive is aVR, **aVL, III,** aVF, II, and I. In Column 3 or the S plane, the order of QRS potentials from negative to positive is aVR, aVL, I, III, aVF, and II. In the 4th column or the X plane, the order of the QRS from negative to positive is III, aVF, II, **I,** aVL, and aVR. (The isoelectric leads are in bold face type.)

Thus in the L, T, S, and X planes, whose electrocardiograms are pictured in Figure 1, leads aVR in the L plane, aVL, and III in the T plane and I in the X plane are essentially isoelectric. The greatest negative potential was recorded in aVF of the X plane, and the greatest positive potential was recorded in lead II of the S plane. The positive direction of lead aVF in the X plane is downward (the negative upward), and the positive direction of lead II in the S plane is from the right forelimb insertion to the interscapular space. Thus one might expect the QRS axis in three dimensional space to point upward and to the left.

QRS Complex: Chest-Leg Leads. Electrocardiograms from unipolar chest leads have been pictured in Column 1 of Figure 2.

Lead axis in unipolar leads is postulated to run from the electrical center of the heart to the position chosen. Inspection of Column 1 shows that QRS potential changes in a progressive manner through the unipolar chest lead positions. QRS complex starts out negative in V_1, is slightly more negative in V_3, is less negative in V_4 and becomes positive in V_5.

Positivity increases progressively in V_7 and V_8 and decreases in V_9; becomes almost zero in V_{11}; and is negative on return to V_1. Change of sign occurs twice, once on each side of the animal. One point of change has been recorded in the isoelectric lead V_{11}. Leads V_1, V_3, and V_4 have a negative QRS potential while V_5, V_7, and V_8 have a positive potential; therefore, a second isoelectric point falls between V_4 and V_5.

Bipolar chest leads are given in Columns 2, 3, and 4 of Figure 2 with right forelimb, left hind limb, and left forelimb respectively serving as the negative electrode position, while the positive electrode is moved around the chest. In all four columns of Figure 2, a change of sign is noted in going from position V_4 to V_5. Another change occurs at V_{11} in the unipolar leads of the first column and the CR_{11} and CL_{11} leads (Column 2, and 4) since QRS in these leads is essentially ioelectric. In Column 3, chest position 11 gives a positive QRS, and chest position 1 a negative QRS. Hence a change in sign occurs in going from position 11 to position 1.

QRS Complex: Chest-Scapular Leads. In Figure 3, the first column contains recordings of the unipolar chest leads when pooled against the Einthoven triangle in the S-series (pooled electrodes at prescapular position, right forelimb, and left forelimb) and is somewhat different from the series recorded when pooled leads are placed on the limbs. (The gap from V_5 to V_9 in Column 1 of Figure 3 can be filled by aVF of Column 3, Figure 1.) However, as was true in Column 1 of Figure 2, the QRS is negative and decreasing through SV_2 and SV_4 to SV_5 where it is almost isoelectric. The S-aVF lead, which can be substituted for V_8, records a positive QRS deflection. S-V_9 is barely positive and shows the transition between positive and negative values to be at a point different from V_{11} where the transition occurs when the leg leads are pooled. In SV_{11} the QRS potential is negative.

In Column 1, 2, and 4 of Figure 3, just as in Figure 2, SV_5 is essentially a point of transition from negative to positive. But SCF_5 in Column 3 is negative as are *all* leads pictured in Column 3. Thus by shifting the negative electrode from the left leg to the prescapular space, the pattern of CF electrocardiograms obtained with chest positions has shifted from an alternating positive-negative pattern to a pattern entirely negative. Such a shift was not noted in the V, CR, or CL series pictured in Columns 1, 2, and 4. (The meaning of these facts will be discussed after the position of the QRS axis in three dimensional space has been calculated.)

Columns 2 and 4 of Figure 3 should be identical with these columns in Figure 2 wherever the bipolar connections of the electrocardiograms selected for illustrations are identical. A comparison of Columns 2 and 4 in Figures 2 and 3 discloses extent to which electrocardiograms can be considered reproducible. Inspection discloses only small differences between Columns 2 and 4 of Figures 2 and 3. Greatest differences are noted in V_4 and V_9. Experience indicates that the differences are due to chest movements, stance, and sometimes slight differences in positions of the electrodes.

In general, the QRS complex provides a galvanometer deflection mainly in one direction. Sometimes the deflection is biphasic, as for example, in leads I and III of the leg leads, lead III, aVL, and aVF of the T plane (Figure 1), in leads CR_T, CL_5, CL_{11}, and CL_T (Figure 2), and in SV_5, SCR_5, SCL_5, and SCL_T (Figure 3); or is isoelectric as in leads X-I, CR_{11}, and S-CR_{11}. Inspection of Figures 1, 2, and 3 indicates that the greatest QRS potential is recorded in SCF_3 of Column 3, Figure 3 or aVF of Column 4, Figure 1. Almost equal is SCF_1 of Column 3, Figure 3.

Visualization of the QRS Axis in Calf F-25: A preliminary visualization of the QRS axis in three dimensional space can be obtained by noting the leads giving the greatest potential and the isoelectric leads or those giving the least potential. If the greatest potential has been recorded, the QRS electrical axis lies along the axis of the lead yielding the greatest potential. The QRS electrical axis also lies along a line perpendicular to the plane of the null band.

On the basis of high potential in S-CF_3 of Figure 3, the QRS axis should make only a small acute angle with the axis of S-CF_3. The axis of S-CF_3 passes through the prescapular position and the C_3 position on the left sternal margin. The axis of X-aVF of Figure 1, which points downward and slightly to the left, also should form only a small angle with the QRS axis. Both S-CF_3 and X-aVF indicate that the QRS axis points dorsad.

If one examines the isoelectric leads of Figures 1, 2, and 3, the following electrode positions are met repeatedly: Left forelimb, right forelimb, dorsal thoraco-lumbar border, C_5, C_9, and C_{11}. If these six positions are placed on a model of a calf, it is clear that they form a narrow band around the calf and lie very near a plane through the left forelimb insertion, through $V_{4.5}$, through C_{11}, and through a point somewhat behind the dorsal thoraco-lumbar border, possibly near the lumbo-sacral border.

All the unipolar isoelectric leads of Figures 1, 2, and 3 have the positive electrode on or very near the null band suggested in the previous paragraph. All the isoelectric bipolar leads except X-I and CF_{11} have both electrode positions on or near this null band. The axis of X-I lies above and at a slight angle to the null band. A possible explanation of X-I being isoelectric is that chest positions C_7 and C_9 are on equipotential bands, and the spread per unit of potential difference is greater on the left side than on the right side.

CF_{11}, from the chest position behind the right olecranon to left hind limb, is also isoelectric in calf F-25. One factor contributing to the small QRS potential in CF_{11} is the wide distance between equipotential lines toward the pubic areas. The QRS complex in aVF of Figure A has a magnitude of -0.2 millivolts. Thus the drop in potential from the null band to the left limb electrode is approximately 2 units (0.1 millivolt = 1 unit).

It is also interesting to compare aVF and T-aVF. In both these leads the electrodes on the forelimbs are pooled. Positive electrode in aVF is on the left hind limb and in T-aVF at the middorsal thoraco lumbar border. QRS is -0.2 millivolts in aVF and 0.05 millivolts in T-aVF. In going from the T position to the left hind limb one crosses only 2.5 equipotential lines. In contrast, when the positive electrode is shifted to the prescapular position (S-aVF), QRS has a value of 0.7 millivolts. Thus in going from T to S, some 6-7 equipotential lines are crossed (one line for each 0.1 millivolt).

A line perpendicular to the plane of the null band (approximately through the left forelimb insertion, the right forelimb insertion, T, C_5, C_9, and C_{11}) points mainly dorsad, somewhat forward and somewhat to the left. But all of the QRS does not project onto the plane of S-CF_3 and X-aVF. aVL indicates that there is a significant component pointing from the electrical center of the heart toward the left forelimb, and aVF indicates a significant component pointing forward (away from the hind limb area). S-CF_3, X-aVF, aVL, and aVF together suggest that the axis will point markedly upward but somewhat forward and somewhat to the left.

Calculation of QRS Vector: If the four lead systems of Figure 1 are utilized to estimate the direction and magnitude of the QRS vector by either the Einthoven triaxial or Pallares hexaxial construction, it soon becomes apparent that only the last two columns (S- and X-planes) produce consistent QRS potentials over an extended series of heart beats. The first two columns (L and T planes) will, due to respiratory effects, often give wide fluctuations in QRS potential and make difficult a precise evaluation of the QRS vector.

The electrical activity of the heart is manifest in three dimensional space, and each lead axis or lead plane records only components of the electrical changes parallel to that axis or plane (17). Because of the high QRS potentials expressed in some leads of the S and X planes, it is apparent that a major component of the QRS axis has been projected onto these planes. It is also apparent that these planes have smaller angles with the QRS axis than have the L and T planes where smaller components have been projected and the angles with the QRS axis approach the perpendicular. Correspondingly, it will be noted that the potentials recorded in the L and T planes are smaller than some of those recorded in the S and X planes.

As previously suggested, one can visualize the orientation of the QRS vector by selecting isoelectric leads in order to draw the null plane. Then one can partially confirm the direction and estimate the magnitude by selecting leads with the greatest potential. The final estimation is usually made geometrically. The QRS vector can be constructed from any three leads not in the same plane. But because of ambiguities previously noted, it is better to use 12 leads (the hexaxial lead system in two planes) to provide the basis of an adequate interpretation of the QRS axis.

The QRS Component in the L-Plane: Amplitudes of the QRS deflection for calf F-25 in the leg lead plane are as follows: (Figure 1): I = 1 mm., II = -2, III = -2, aVR = 0, aVL = 4, and aVF = -2. When the unipolar values are multiplied by a factor of 1.15, magnitudes become aVR = 0, aVL = 4.6, and aVF = -2.3. These values are plotted on the spokes of the hexaxial system. Perpendicular lines are constructed through each point on its respective axis. Since there is no common point of intersection of the perpendiculars, two triangles are constructed, one for perpendiculars to the bipolar leads and one for the unipolar leads (Figure 6A). According to these triangles, the vector could be oriented somewhere in the area between 30° to 90°; the Z component would lie between 0 and 4.2; and the X component between 1.5 and 4.6. Experimental error in the sampling technique as well as respiratory movement can lead to wide variation in the L plane.

The QRS Component in the S-Plane: Amplitude of the QRS excursions in the S-leads are (Figure 1, Column 3): S-I = 3, S-II = 8.5, S-III = 5.5, S-aVR = -5, S-aVL = -2, S-aVF = 7. Multiplying unipolar leads by 1.15 changes the last three values to -5.75, -2.30, and 8.05. When these values are plotted on the hexaxial spokes (Figure 5A), and perpendiculars are constructed at the points plotted (Figure 5B), two points of intersection are obtained, one for the bipolar leads and one for the unipolar leads. The angle of the bipolar vector projection is 69° and the magnitude 0.86 mv., while the unipolar vector projection has an angle of 77° with a magnitude of 0.84 mv. Averages between the two values, 73° and 0.85 mv., are taken as the direction and magnitude of the QRS axis in the S-plane.

Another method to approximate the vector component position is mentioned by Goldberger (16, page 441) and requires simple graph paper instead of polar coordinate paper. Two leads are selected 90° apart, and their potentials are plotted on the rectangular coordinates (Figure 5D). By the Goldberger method the QRS vector component is found to be 8.7 units at an angle of 70°. Goldberger values are sufficiently close for many clinical purposes, but not for the determination of more precise relationships such as genetic factors.

The QRS Vector in Three Dimensions: By projecting the vector component onto the Z axis (equivalent to the axis of lead I) we obtain $z = 2.4$, while a projection on the y axis (equivalent to the axis of S-aVF) yields $y = 8.1$. $z = 2.4$ is compatible with the range 0-4.2 and is accepted because there is less change due to respiratory movement in the S-lead plane than exists in the L-plane. The aVR lead has zero (less than 0.05 mv.) potential and therefore the axis projection in the L-plane is perpendicular to aVR. A value of 60° for the vector direction in the L plane and a z value of 2.4 yield a projection on the X-axis of 4.0 and a vector length of 4.7 (0.47 mv.). The x, y, and z components of the QRS vector for calf F-25 are then -4.0, 8.1, and 2.4, respectively.

By use of the three dimensional extension of the Pythagorean theorem (Equation 1):

$$V_{QRS} = \sqrt{x^2 + y^2 + z^2}$$
$$= \sqrt{(-4.0)^2 + (8.1)^2 + (2.4)^2} = \sqrt{87.36}$$
$$= 9.3 \text{ units or } 0.93 \text{ mv.}$$

Thus the azimuth angle in the leg lead plane is 60° with a projection length of 4.7 ($\sqrt{x_1^2 + z_1^2}$); and the length of the radius vector is 9.3. To find the elevation one uses equation 2.

$$\cos \phi = \frac{p}{r} = \frac{4.7}{9.3} = .5053, \text{ and } \phi = 60°$$

Thus the QRS vector for calf F-25 may be expressed as

$$V_{QRS} = -4.0\,\mathbf{i} + 8.1\,\mathbf{j} + 2.4\,\mathbf{k};$$

the vector may also be expressed as having an azimuth angle of 60° from the left arm toward the head in the leg lead plane, a 60° angle of elevation, and a radius vector length of 9.3 units or 0.93 millivolts. The vector points dorsad, caphalad, and to the left.

T Complex: Voltage of the T wave varies from 0 to 0.45 millivolts. Higher voltages are recorded in T-II, S-II, SCF_1, and SCF_3, with the highest in SCF_1. A maximum duration of 0.14 seconds was recorded in SCF_1. Shorter intervals were found in other leads and indicate the recording of an isoelectric portion of the T complex in many of the leads. For comparison, the QRS complex had a duration of 0.10 second and a maximum potential of 1.4 millivolts.

Generally the T-complex, as did the QRS complex, provided a monophasic galvanometer deflection. Usually the T complex and the QRS complex had opposite signs. The T-complex of F-25 is biphasic in leads III, CR_3, CL_4, S-CR_3, and S-CF_T. The biphasic T complexes are small and have almost equal positive and negative components, and thus are nearly isoelectric.

T-Wave Null Band. The T-wave is isoelectric in bipolar leads III and X-I of Figure 1. The axes of these leads are therefore essentially perpendicular to the average T-wave vector or make only a small angle with the null plane of the T-wave electrical vector. Additional isoelectric bipolar leads can be found in Figures 2 and 3, or their location can be predicted by noting where the T complex changes sign. (Where it is obvious that the isoelectric position would fall between two electrode positions, the hypothetical intermediate position will be indicated by placement in parenthesis.) The following bipolar leads in Figures 2 and 3 are essentially isoelectric: CR_3, CR_{11}, CF_4, (CF_{10}; since CF_9 is negative while CF_{11} is positive), CL_4, (CL_{10}), S-CR_3, S-CR_{11}, S-CL_4, (S-CL_{10}), and S-CF_T.

It will be recalled that axes of unipolar leads that are isoelectric are not only perpendicular to the vector, but must also lie on the null-band for the T-wave. The unipolar isoelectric leads for the T complex are T-aVL, S-aVL, V_4, and V_{11}. From these leads it can be seen that the null band of the T complex passes very near V_4, V_{11}, and the site of the left forelimb insertion. More rigidly the null band will pass slightly below V_4, slightly above V_{11} and, as nearly as can be determined, through the left forelimb insertion. This implies considerable elevation anteriorly because V_4 and V_{11} are under the olecranons of the forelimbs. The null plane will pass below the insertion of the left hind limb, because aVF has a recordable negative potential. Thus the plane of the null band rises slightly from left to right, but falls sharply from front to rear.

Of the bipolar leads, CF_T has a very small potential partly because both electrodes lie distant from the heart, but mainly because the C_T and F electrode positions are essentially equipotential with an axis somewhat paralleling the null plane. The leads CR_{11}, CL_4, S-CR_{11}, and S-CL_4 are from pairs of electrodes which are close together and at the same time on or near the null band. The leads CR_3, CF_4, (CF_{10}), (CL_{10}), S-CR_3, and (S-CL_{10}) are isoelectric leads running between sets of equipotential, but not necessarily zero potential, points.

Because of the low potential gradient of the T complex, equipotential contour lines are far apart on the surface of the calf. The maximum T-wave potential recorded is only 0.45 millivolts, and thus only 5-6 equipotential lines one unit (0.1 millivolt) apart will appear on the surface of the calf. Leads with both electrodes above the null band plane would tend to be isoelectric or of small potential in the T complex because of the low potential gradient above the plane. Below the plane the gradient of potential is higher and the space between equipotential lines is less. The probable explanation of the more frequent lines below the plane is the nearness of the cardiac apex.

In all columns of Figure 2 and in Columns 1, 2, and 4 of Figure 3, the sign of the T wave changes as the chest electrode is shifted from V_1 to V_{11}. But in Column 3 of Figure 3, the T complex is positive throughout. Since V_s was the most negative unipolar position, bipolar chest leads (the chest lead always has the positive connection to the recording device) will always give a positive T wave when paired with the scapular lead V_s. It will be recalled that the QRS complex in Column 3 of Figure 3 also did not change sign, but was negative throughout.

Calculation of the T-Complex Vector: The greatest potential of the T wave was 0.45 millivolts and occurred in S-CF_1. Thus, as a first approximation, a line running from the scapular position V_8 to the right sternal margin may be taken as the direction of the electrical axis of the T complex. The maximum potential suggests a direction mainly ventrad and slightly to the right, with no clear cut cephalo-caudad component. The null plane suggests a direction mainly ventrad, slightly to the right, and somewhat forward.

Magnitude and direction of the T-complex vector can be evaluated more precisely as was done for the QRS vector. Amplitude of the T-complex *in the L plane* is as follows: I = —1.5, II = —2, III = 0, aVR · 1.15 = 1.8, aVL · 1.15 = —1.15, aVF · 1.15 = 1.8. When these values are plotted on hexaxial coordinate paper, the perpendiculars to the unipolar axes form a small triangle, and the perpendiculars to the bipolar axes form a very small triangle (Figure 6A). The unipolar lead triangle provides a range from 129° to 157° for the position of the vector, as projected onto the L plane. The bipolar triangle provides a range from 140° to 150°. It is apparent that the axis is directed forward and to the right of the calf. An average of 129, 157, 140, and 150 yields 144°.

In the S-plane, the potential of the T-complex is as follows: S-I = —1.5, S-II = —3, S-III = —2.1, S-aVR · 1.15 = 3.45, S-aVL = 0, S-aVF · 1.15 = 2.9. With these values the plotting procedure leads to two small triangles and shows that the T-complex axis is directed downward and to the right. As four of the perpendiculars intersected over a very small area, the line drawn to the center of this area was chosen as the T wave vector in the S-plane. As plotted, the angle of the T axis with the line of the reference was —117°; the length of the vector projection was 3.3 units or 0.33 mv.; the Z component was —1.4; while the Y component was —2.8. From leads I and S-I, Z should equal 1.5 units. This experimental value was chosen instead of the construction value of —1.4. The shift from —1.4 to —1.5 alters the angle of the T axis in the S plane to —118°.

In the leg lead plane, the —144° angle of projection of T vector, along with a Z component of 1.5, yields an X component of —1.2 units and a vector projection length of 2.0 units or 0.2 mv.

By the use of Equation 1

$$V_T = \sqrt{x^2 + y^2 + z^2}$$
$$= \sqrt{(-1.2)^2 + (-2.8)^2 + (-1.5)^2}$$
$$= \sqrt{11.53} = 3.4 \text{ units} = 0.34 \text{ millivolts}$$

The value for V_T is 0.34 mv. The depression of the T axis from the plane of the leg leads may be found with Equation 2.

$$\text{Cos } \phi = \frac{a}{h} = \frac{2.0}{3.4} = .5882$$

$$\phi = 54°$$

Thus the T-wave is depressed 54° below the plane of the leg leads. Hence the T wave vector for calf F-25 may be expressed as —1.2 **i** —2.8 **j** —1.5 **k**. The vector may also be expressed as having an azimuth angle of 144° from the left arm (rotating from the left arm toward the head and then toward the right arm) in the L plane, an angle of depression of 54° below the L plane, and a radius vector length of 3.4 units or 0.34 millivolts.

QRS-T Angle: Casual inspection of the various leads indicates that the T wave does not have a maximal excursion in the same lead as the QRS complex, and that there is a difference in the vector direction between the QRS and T complexes. In human electrocardiography (13, p. 93) the QRS and T-waves are usually concordant (have the same sign) but for F-25, and for cattle in general, the QRS and T complexes are for the most part discordant (have opposite sign). However, concordant QRS and T complexes may be found in leads II, aVF, V_4, CR_4, CF_{11}, SV_T, and S-CR_4. In all these leads the potential recorded is small.

Since the QRS and T vectors can be represented by lines which intersect, there will be an angle between them. This QRS-T angle is of importance in human electrocardiography. In normal human hearts the angle between the QRS and T vectors usually is less than 60°. The angle increases with right or left ventricular hypertrophy. In normal beef calves of 500 or 800 pounds body weight, the angle between the QRS and T vectors is definitely greater than 60°.

The law of cosines (26) gives the angle between two lines, OP_1 and OP_2:

$$2r_1r_2 \cos\theta = r^2_1 + r^2_2 - d^2 \qquad \text{(Equation 3)}$$

where r_1 and r_2 are the radius vectors of points P_1 and P_2, d is the distance between the two points, θ the angle between the lines, and

$$r^2_1 = x^2_1 + y^2_1 + z^2_1 \qquad \text{(Equation 4)}$$

$$r^2_2 = x^2_2 + y^2_2 + z^2_2 \qquad \text{(Equation 5)}$$

$$d^2 = (x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2 \qquad \text{(Equation 6)}$$

By substituting the x, y, and z equivalents for the radius vectors and for d in Equation 3, one achieves Equation 7:

$$r_1\, r_2 \cos\theta = x_1\, x_2 + y_1\, y_2 + z_1\, z_2 \qquad \text{(Equation 7)}$$

In Equations 3 to 7, r_1 is the radius vector of the QRS complex (V_{QRS}), while r_2 is the radius vector of the T complex (V_T). The formula to determine the QRS-T angle now becomes:

$$\text{Cos (QRS, T)} = \frac{x_1\, x_2 + y_1\, y_2 + z_1\, z_2}{V_{QRS} \cdot V_T} \qquad \text{(Equation 8)}$$

Using this formula, and substituting the previously determined values for the x, y, and z coordinates, one finds:

$$\text{Cos (QRS, T)} = \frac{(-4.0 \cdot -1.2) + (8.1 \cdot -2.8) + (2.4 \cdot -1.5)}{9.14 \cdot 3.39}$$

$$= \frac{21.48}{30.98} = -0.69333$$

Angle (QRS, T) = 134°

where the angle measured is the smaller angle obtained on rotating the QRS vector to the T vector.

Thus the QRS vector and the T vector of calf F-25 have an angle of 134° between them.

P-Complex: Voltage of the P-wave varies from 0 to 2.0 millivolts. The higher voltages were recorded in S-CF_4, S-CF_3, and S-CF_1, with the highest in S-CF_4. Thus the P-wave vector is oriented from the scapular position to the chest position under the olecranon, or mainly dorso-ventrally. The P-wave was of very small amplitude in the majority of electrocardiograms recorded in Figures 1, 2, and 3. A maximum duration of 0.10 second for the P-wave was recorded in S-CF_1. Shorter intervals were found in other leads and indicated the recording of an isoelectric portion of the P complex in many of the leads. Generally the P-wave provided a notched or diphasic galvanometer deflection in leads whose axes were oriented dorso-ventrally. Good examples of the notched P-wave are given in S-II, S-III, X-II, X-III, S-aVF, and X-aVF.

Though small and difficult to measure, the direction and magnitude of the P-complex vector may also be estimated. It is to be realized that the accuracy is of a low order. Yet, when comparing certain diseased states with normals, a marked difference can be noticed beyond the error of measurement and individual variability in normal animals.

Null Plane of P-Complex: Although the P-complex has little potential in most leads, the null-band can be located as has been done for the QRS and the T-waves. The leads of the T-plane in general have a small potential; consequently the T plane will be approximately parallel to the plane of the null band. From the unipolar chest leads it can be seen that the null band will pass very close to V_6, V_9, V_T, S-V_6, and S-V_9. The null plane thus rises rapidly from front to back and has no determinable slant from right to left. The vector perpendicular to the null plane points ventrally and to the rear.

P-Complex Component in the L Plane: In the L-plane (Figure 6A) the potentials of the P-complex are as follows: I = 0.5, II = 1.0, and III = 0.5 units. After multiplying the unipolar leads by 1.15, aVR = —0.5, aVL = —0.2, and aVF = 0.5. (It should be recalled that generally measurements are made only to 0.5 unit, and the percentage error increases markedly with potentials of less than 0.5 unit.)

When the potentials are plotted on the respective leads and perpendiculars drawn, four of the six perpendiculars pass through the unipolar lead point (Figure 6A). For this point OX equals 0.8, the angle is +79°, and OZ is 0.16 from OX and the angle. (If the vector components are greater than two units (0.2 millivolts) the x, y, or z components are read directly, and the angle is calculated. If any component is less than two units, the most satisfactory approximations for a vector component and the angle, or for the two vector components are obtained. The angle or remaining vector can then be calculated.)

P-Component in the S-Plane: The magnitude of the P-complex in the leads of the S-plane are as follows: S-I = 0.2, S-II = —1, S-III = —1.2; while the corrected values for the unipolar leads are: S-aVR = 1.0, S-aVL = 1.1, S-aVF = —1.1. Perpendiculars to the bipolar leads and to one unipolar lead meet at a point whose vector projection on the Y-axis is —1.4 and whose angle is —83.5°; and z is again calculated to equal 0.16. V_p becomes 1.62 units. The cosine of the angle of depression is 0.8/1.62 or 0.491, and the angle of depression 60.5°.

P-wave Vector: Hence the P-wave vector for calf F-25 may be expressed as $0.8\mathbf{i} - 1.4\mathbf{j} + 0.16\mathbf{k}$. The vector may also be expressed as having an azimuth angle of +79° from the left arm (rotating from the left arm toward the tail) in the L plane, an angle of depression of 60° below the L-plane, and a radius vector length of 1.6 units or 0.16 millivolts.

X-Plane: The plane of the X-leads is not at right angles to the other leads in this discussion, but could be utilized in the axis calculations by simple geometric means. Because it is easier to use planes 90° apart, only the L- and S-planes are studied routinely. While the X-plane has not been used extensively in our study of bovine electrocardiograms, it deserves consideration because of the clarity of the recordings. In most leads, potentials from striated muscle interfere with interpretations of the electrocardiogram. Effects of muscle tremor are very small in the X-plane.

QRS Component in the X-Plane: Potentials recorded for QRS in the X-plane are: X-I = 0, X-II = 10, X-III = 11. The corrected unipolar potentials are as follows: X-aVR = 5.75, X-aVL = 6.3, X-aVF = 12.6. The QRS component lying in the X-plane has a magnitude of 12.6 units (1.26 millivolts), and is directed dorsally at an angle of —90° with the line of reference. The line of reference runs from the dorsal angle of the left to the dorsal angle of the right scapula. 0° points to the left, and positive angles are inscribed ventrally and negative values dorsally (Figure 6C).

The —90° value differs from the 73° value of the S-leads, but this difference is to be expected because the S-lead plane LL electrode is located mid-dorsally. For the X-lead, it is not mid-ventral but at the left sternal margin. Because of the inversion of the Einthoven-type triangle with respect to the S-lead triangle, the vector which is directed dorsally in the animal is recorded negatively in the X-series but positively in the S-series.

T-Component in the X-Plane: The T potentials recorded in the X-lead are: X-I = 0, X-II = 3.5, X-III = 3.5; corrected unipolar leads: X-aVR = —1.5, X-aVL = —2.3, X-aVF = 4. Four of the perpendiculars intersect at a point four units from the origin (0.4 millivolts) and at an angle of 90° with the line of reference (Figure 6C). The QRS and T components in the X-plane run in diametrically opposite directions.

P-Component in the X-Plane: The P-wave potentials in the X-plane are: X-I = 0.2, X-II = 1.3, X-III =1.1, X-aVR (corrected) = —0.6, X-aVL = —0.3, and X-aVF = 1.0. The P vector in the X-plane is 1.6 units or 0.16 mv. and is directed 74° downward, and points slightly to the left (Figure 6C).

Semisagittal Plane: A side or sagittal view of the vector projections is sometimes desirable for easy viewing of the spatial relationships. From the series of exploratory leads a plane can be constructed by using leads III (left forelimb, left hind limb), S-III (left forelimb, scapular position), and CF_8 (scapular position, left hind limb). Because the plane constructed from these leads is canted, the label semisagittal (SS) plane has been tentatively chosen. The anatomical axis of the heart is approximately parallel to this plane.

QRS-Component in the SS Plane: The QRS potentials are: III = —2, S-III = 5.5, CF_8 = 9.5. The QRS wave vector component lies between 65-78°. While the measured QRS potential for lead III has been taken from Figure A, the QRS potential in this lead varies with respiration, and a segment with a potential of —4 or even —5 could have also been selected. If lead III = —4 units is used for the plotting, a point intersection between the perpendiculars is obtained and the angle of the vector component lies 65° above the line between the left limb insertions with a length of 9.2 units (0.92 mv.). These values are in close agreement with the previously obtained elevation angle of 60° with an absolute vector magnitude of 9.3, and they indicate that the cardiac QRS vector makes a small angle with semisagittal plane (Figure 6B).

T-Component in the SS Plane: The T potentials recorded in the semisagittal plane are: III = 0, S-III = —2.1, CF_8 = —2.2. The T vector component in this plane has a potential of 0.25 mv. and is pointed directly ventrad, making an angle of —90° with the line of reference. Because of the angle that the semisagittal plane makes with the T-wave vector, only 73% of the vector is recorded in this plane (Figure 6B).

The P-Component in the SS Plane: Values of the P potentials recorded in the semisagittal plane are: III = 0.5, S-III = —1.2, CF_8 = —1.7, and give a vector component of 0.18 mv. directed —105° from the line of reference, or downward and slightly to the rear (Figure 6B).

QRS Vectors in E Calves

Information compiled on each calf includes net QRS potentials in leads I, II, III, S-I, S-II, S-III and CF_8 of electrocardiograms taken at 500 and 800 pounds body weight. QRS angles were calculated in the L plane, S plane, and SS (semisagittal) plane. Tabulations of the data have been made to facilitate comparison between sexes within lines, within sexes between lines, and an overall sex comparison. There were 21 male and 12 female Herefords in three breeding lines available for this study.

QRS Potentials: The tabulated data on net QRS potentials from the E calves can be seen in Table 1. The greatest potentials were recorded in CF_8. Fair potentials were recorded in leads S-II

Table 1. AVERAGE QRS POTENTIALS IN E CALVES.
A. At 500 Pounds

	No. of Calves	Leg Leads			S-Leads			CF_8
		I	II	III	S-I	S-II	S-III	
Lionheart								
Male	5	—2.4	—5.2	—2.8	—2.0	5.2	7.2	8.9
Female	5	—1.2	—1.2	0.2	—1.4	5.9	7.4	8.7
Prince								
Male	9	0.5	—1.3	—0.8	0.8	7.2	6.3	8.7
Female	3	—0.6	—2.3	—1.5	0.2	6.6	6.3	7.6
David								
Male	7	0.1	—4.1	—1.1	—1.2	6.3	7.1	9.5
Female	4	—2.1	—2.7	—2.8	—2.5	6.2	8.0	9.2
Totals								
Male	21	—0.3	—3.1	—1.3	—0.5	6.4	6.8	9.0
Female	12	—1.4	—2.0	—1.2	—1.4	6.2	7.3	8.6
All	33	—0.7	—2.7	—1.3	—0.8	6.3	7.0	8.8

B. At 800 Pounds

	No. of Calves	Leg Leads			S-Leads			CF_8
		I	II	III	S-I	S-II	S-III	
Lionheart								
Male	5	—3.0	—5.0	—2.6	—2.5	5.8	8.0	10.2
Female	5	—0.8	—2.2	—0.6	—1.7	5.0	6.4	8.1
Prince								
Male	9	0.6	—1.5	—1.7	1.0	7.2	6.1	8.8
Female	3	—1.0	—1.0	—0.3	0.3	6.0	5.6	6.6
David								
Male	7	—1.7	—3.1	—1.3	—0.8	6.4	7.1	8.6
Female	4	—1.2	—3.2	—1.2	—1.2	6.2	7.2	8.8
Totals								
Male	21	—1.0	—2.9	—1.8	—0.5	6.6	6.8	9.1
Female	12	—1.0	—2.2	—0.7	—1.0	5.7	6.5	8.0
All	33	—1.0	—2.6	—1.4	—0.6	6.2	6.7	8.7

The potentials recorded in this and other tables are in potential units. Multiply by 0.1 to obtain millivolts.

and S-III. All these leads involve a scapular electrode, the other electrode respectively being placed on left rear limb, right forelimb, and the left forelimb. Standard leg leads gave very low potentials.

Variation in QRS Potentials: Standard deviations of net potentials in the various leads are given in Table 2. There was a greater variability in the leg lead potentials recorded from calf to calf than were found in the scapular lead potentials from calf to calf. It will be recalled that leads I and S-I have identical electrode positions.

Variations in leads I and S-I were less than the variation in leads II and III. Leads S-II and S-III have less variation than leads

Table 2. STANDARD DEVIATIONS (S.D.) AND COEFFICIENTS OF VARIATION (C.V.) OF QRS POTENTIALS AND ANGLES IN E CALVES

	500 lbs.		800 lbs.	
	S. D.	C. V.	S. D.	C. V.
I	2.18	3.1	1.48	1.48
II	2.83	1.04	3.38	1.3
III	3.07	2.36	2.72	1.94
S-I	1.72	2.15	1.67	2.78
S-II	1.20	0.19	1.05	0.16
S-III	1.45	0.207	1.18	0.17
CF_8	1.58	0.18	1.98	0.22
QRS angle				
S Plane	11.5	0.12	12.0	0.13
SS Plane	10.9	0.14	12.0	0.15

Table 3. ANALYSIS OF VARIANCE OF THE QRS POTENTIALS AND ANGLES AT 500 POUNDS BODY WEIGHT

	Mean Squares			
	Sex	Line	Sex x Line Interaction	Error
Degrees of Freedom	1	2	2	27
Potentials in				
Lead I	1.28	2.25	0.48	4.31
Lead II	5.20	1.47	2.26	7.03
Lead III	0.40	0.02	1.25	10.25
Lead S-I	0.53	3.92	0.16	1.77
Lead S-II	0.01	0.01	0.001	1.25
Lead S-III	0.30	0.74	0.004	2.19
Lead CF_8	0.46	0.32	0.06	2.70
Angles in				
S Plane	0.72	297.13*	2.97	64.24
SS Plane	32.22	0.29	2.46	140.26

* Significant at the 5 percent level.

Table 4. ANALYSIS OF VARIANCE OF THE QRS POTENTIALS AND ANGLES AT 800 POUNDS BODY WEIGHT

	Mean Squares			
	Sex	Line	Sex x Line Interaction	Error
Degrees of Freedom	1	2	2	27
Potentials in				
Lead I	0.08	3.04	1.69	1.49
Lead II	2.75	4.36	0.48	6.64
Lead III	0.17	0.23	0.03	7.73
Lead S-I	0.0009	5.61	2.51	1.60
Lead S-II	1.18	1.05	0.87	0.76
Lead S-III	0.95	1.42	0.13	1.01
Lead CF_8	4.39	1.55	0.0004	2.16
Angle in				
S Plane	4.92	267.61	15.17	79.10
SS Plane	2.72	2.97	20.66	147.21

I, II, and III. The variation problem is amplified if relative changes are considered. Because of the low potentials in leads I, II, and III, the coefficient of variation (standard deviation over the mean) ranges from 1.48 to 3.1 in leads I, II, and III. In the scapular leads, the coefficient of variation ranges from *0.16* to *0.22*.

Body Weight, Line and Sex Components: The least squares method of analysis (4) was used to estimate the line, sex, and line x sex interaction components for the QRS potentials recorded from seven leads and for the QRS angle in two planes. Each observation was assumed to be the sum of the influences of other variables as follows:

$$Y_{ijk} = M + S_i + L_j + (SL)_{ij} + e_{ijk}$$

where Y_{ijk} = the observation on the *kth* calf of the *ith* sex in the *jth* line.

M = the overall effect.

S_i = the added effect of the *ith* sex.

L_j = the added effect of the *jth* line.

$(SL)_{ij}$ = the added effect of the *ith* sex in the *jth* line.

e_{ijk} = random error.

Differences were determined between the estimates of the effects of each line and of each sex and were tested for significance at the 5 and 1% levels of probability. Analysis of variance data on QRS potentials at 500 and 800 pounds body weight are given in Tables 3 and 4.

Table 5. Correlation Coefficients for QRS Potentials and Angles

Upper Right: 500 #

	Lead Potentials							S-Plane < of Axis	SS-Plane < of Axis
	I	II	III	S-I	S-II	S-III	CF_8		
I	0.61**	0.42	—0.12	0.65**	0.50**	—0.23	0.13	—0.82**	—0.07
II	0.51**	0.69**	0.54**	0.39*	0.47**	0.00	—0.33	—0.38*	0.21
III	0.08	......	0.16	—0.03	0.25	0.29	—0.46*	—0.015	0.54**
S-I	0.76**	......	......	0.74**	......	......	......	—0.92**	......
S-II	0.39*	......	......	......	0.67**	0.32	0.09	—0.15	......
S-III	—0.56**	......	......	......	......	0.54**	0.19	0.54**	......
CF_8	—0.20	......	......	......	......	......	0.66*	0.02	......
S-Plane	—0.69**	—0.44*	—0.07	—0.97**	—0.67**	0.68**	0.11	0.80**	0.30
SS-Plane	—0.23	0.45*	0.66**	—0.35	0.09	0.42*	—0.40*	0.27	0.56**

Lower left: 800#

* Absolute magnitudes above 0.34 are significant at the 0.05 level.

** Absolute magnitudes above 0.44 are significant at the 0.01 level.

Table 6. REGRESSION COEFFICIENTS FOR QRS POTENTIALS AND ANGLES $y = a + b\,x$

Abscissa Potentials		Ordinates Potentials		a	b	95% confidence limits
I	500 pounds	I	800 pounds	—0.67	0.47	±0.22
II	"	II	"	—0.87	0.64	±0.25
III	"	III	"	—0.84	0.43	±0.27
S-I	"	S-I	"	—0.02	0.73	±0.24
S-II	"	S-II	"	2.48	0.59	±0.24
S-III	"	S-III	"	3.62	0.44	±0.25
CF_8	"	CF_8	"	2.72	0.68	±0.28
Angles		Angles				
in S-Plane 500 pounds		in S-Plane 800 pounds		13.93	0.84	±0.23
in SS-Plane 500 pounds		in SS-Plane 800 pounds		31.07	0.61	±0.34
Potentials		Potentials				
I	500 pounds	S-I	500 pounds	—0.44	0.51	±0.22
I	800 "	S-I	800 pounds	0.16	0.76	±0.24

The analysis indicated statistically significant differences in potentials did not exist between data taken at 500 and at 800 pounds body weight. There were no statistically significant sex or line differences in potentials (a significant line difference in QRS angles will be discussed later).

Correlations Between QRS Potentials: 500 vs. 800 Pounds: Selected correlation coefficients were determined for values where physiological significance was expected or where interpretation was simple. Thus correlation was studied between potential data collected at 500 pounds and data collected at 800 pounds. The correlation coefficients are given in Table 5. Coefficients in the diagonal line from upper left to lower right (*italicized*) show comparisons for specific leads between the potentials obtained at the two weights. All coefficients on the diagonal line, except for lead III, were statistically significant at the 0.01 level.

Regression coefficients corresponding to some of the statistically significant correlation coefficients of Table 5 are given in Table 6. The slopes of the regression lines comparing potentials in given leads at 500 pounds against potentials at 800 pounds were all positive and ranged from 0.44 to 0.73. In general, the greater the correlation coefficient, the greater was the regression coefficient. The A or intercept values fell into two groups corresponding somewhat to the mean potentials in the various leads. Thus for leads I, II, III, and

S-I, the intercepts ranged between —0.016 and —0.872; while for leads S-II, S-III, and CF_8 the intercepts ranged from 2.48 to 3.62 units.

Potentials observed at 800 pounds were thus related to the potentials observed at 500 pounds (except in lead III). In general, low potentials (algebraically) at 500 pounds were accompanied by low potentials at 800 pounds; and high potentials were associated with high potentials. Potentials in leads I, II, III, and S-I tended to be higher at 500 pounds than at 800 pounds body weight. For leads S-II, S-III, and CF_8, low potentials at 800 pounds were above the equivalent potentials at 500 pounds, but high potentials at 500 pounds were below the potentials recorded at 800 pounds. For these three leads the intercept value is high and y increases only from 0.44 to 0.68 as x increases from zero to one. Thus potentials at 500 pounds are related to potentials at 800 pounds, but the potentials at 800 pounds do not reproduce the potentials at 500 pounds.

Lead III potentials at 500 pounds were not correlated with the potentials at 800 pounds. In our experience, lead III shows spontaneous variation in potential due to respiration and body position, and this variation does not follow a reproducible pattern. Other factors in the failure of correlations are the low magnitudes of the potentials and their high coefficient of variation.

Correlations with Potentials of Lead I: Lead I potentials were most highly correlated with S-I potentials. This was to be expected in that electrode positions are the same in I and S-I. However, a lapse of time occurred between recording leads I and S-I and the standing position of the calf may have changed or respiration may have altered. Thus recordings from leads I and S-I should be similar but not necessarily identical.

Since leads I and S-I are identical leads, it might be expected that the equation relating potentials would read that

$$P(I) = 1.0 \times P(S\text{-}I)$$

Potentials in lead I equal 1.0 times potentials in lead S-I. The regression equations obtained however, were:

$$500 \text{ pounds: } P(I) = -0.44 + 0.51 \times P(S\text{-}I)$$

$$800 \text{ pounds: } P(I) = 0.16 + 0.76 \times P(S\text{-}I)$$

The regression coefficient 0.76 is barely significantly different from 1.0 at the 5% level, and one might interpret the regression line as not differing significantly from a regression line with a slope of 1.0. But 0.51 is clearly statistically significant at the 5% level, and data collected from lead I are not as closely related to lead S-I as one might wish. Possibly the younger calves were more disturbed when records were taken as lead I than several minutes later when presumably the identical lead was rerun as S-I.

Lead I potentials were also correlated with lead II and S-II potentials at both 500 and 800 pounds body weight. Lead I potentials were not correlated with leads III, S-III, and CF_8 at 500 pounds, and leads III and CF_8 at 800 pounds. At 500 pounds body weight lead I potentials were not correlated with S-III, but at 800 pounds the correlation coefficient was highly significant at —0.56.

Correlations with Potentials of Lead II: Lead II potentials at 500 pounds are highly correlated with lead III and S-II, and somewhat correlated with leads I and S-I, but not at all with lead S-III. The failure of correlation with lead S-III probably resides in the fact that leads II and S-III are perpendicular to each other. Yet other factors are involved, since S-II and S-III make similar angles with lead I, but I and S-II are correlated while I and S-III are not correlated. (The meaning of these correlations deserve further study. Some of the interrelationships probably depend upon relative positions of the QRS vector in space and the axes of the leads. The unequal distribution of cardiac mass to the right and left half of the calf may also be involved.)

QRS Angles: S Plane: The QRS angle in a given plane may be determined by plotting the potentials obtained in three leads of

Table 7. The Average QRS Angles in the S and SS Planes

Line	No. Animals	Cross-sectional plane (S) Axis Angle		Semi-saggittal plane (SS) Axis Angle	
		500 Lbs.	800 Lbs.	500 Lbs.	800 Lbs.
Lionheart					
Male	5	105.0	107.0	80.0	79.4
Female	5	100.2	102.6	81.0	78.6
Total	10	102.9	104.8	80.5	79.0
Prince					
Male	9	83.3	82.0	76.7	74.1
Female	3	83.6	90.6	83.0	82.0
Total	12	83.4	84.2	78.3	76.0
David					
Male	7	98.5	95.8	78.4	83.1
Female	4	102.0	98.5	81.0	85.0
Total	11	99.8	96.8	79.7	83.5
Males	21	93.7	92.6	78.0	78.3
Females	12	96.6	98.3	81.8	81.6
All Animals	33	95.8	94.4	79.4	79.5

All data are in degrees.

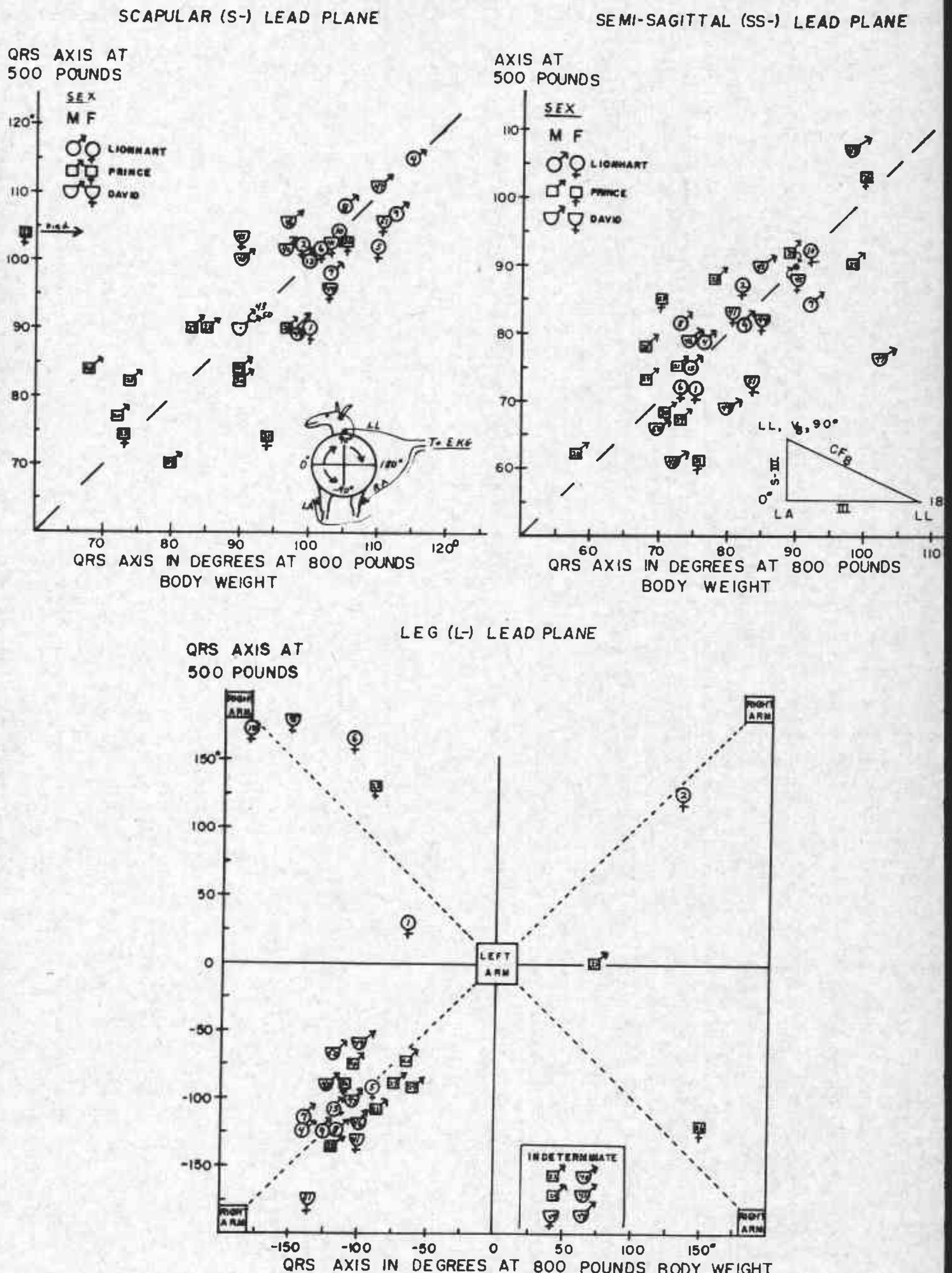


Figure 7. Relationships between QRS axis at 500 and 800 pounds body weight.

the Einthoven triaxial system. The 7 leads of Table 1 provide the necessary background data for each of the three planes: Leg lead (L), transverse (S), and semi-sagittal (SS). Table 7 gives the QRS angle in the S and SS planes. The average QRS angle in the S plane shows little change between 500 and 800 pounds. In the S plane the QRS angle was not significantly different in males and females. However, Prince calves had smaller QRS angles than did the Davids or the Lionhearts (Figure 7, Scapular Leads).

An analysis by Manning (25) of the QRS angle in the S plane of E and F calves indicated line and sex differences of statistical significance. Manning used the hexaxial system and thus established the angles somewhat more critically. A balanced statistical design in Manning's study also gave a reduction in the error component of the variance.

The QRS axis angles at 500 pounds body weight in the S plane have been plotted for the individual calves against angles at 800 pounds body weight (Figure 7). Data from 500 pounds body weight have been plotted on the ordinates and data for 800 pounds body weight on the abscissae. For the S plane the zero degree reference line points to the left, positive angles are upwards, and negative angles downward. All QRS angles in the S plane were positive and ranged from 70° to 115° at 500 pounds and from 68° to 115° at 800 pounds.

An analysis of variance indicated no significant difference between data at 500 and at 800 pounds body weight. An analysis of the regression coefficients showed that the slope of the regression line between 500 and 800 pound data was not significantly different from 1.0. Thus a 45° line has been drawn to indicate the position of points of equal magnitude at 500 and 800 pounds. Angles which were greater at 500 pounds are plotted above the 45° line, and angles which were greater at 800 pounds are plotted below the 45° line.

Obviously the QRS angle in the S plane increased from 500 to 800 pounds body weight in many calves and decreased in others. The possibility exists that the inherent errors in the technique result in a distribution of points on both sides of the 45° line, and give rise to randomly distributed errors which contribute to the variance. Thus, in a given calf, the potential sometimes increases and sometimes decreases as body weight changes from 500 to 800 pounds body weight.

All calves of the Prince line (indicated by the squares in Figure 7), except two had low values (68° to 94°) of the QRS angle in the S plane at both 500 and 800 pounds body weight. Thus the points representing the Prince calves form an isolated group in the lower left corner of the graph. However, the other two Prince female calves had QRS angles of 103° to 105°. Both of the calves were chronic bloaters, and one died before attaining 800 pounds body weight.

None of the animals in the David or Lionheart line had QRS angles in the S plane less than 90°, except E-40, a calf which had a series of complex heart anomalies to be described in a separate publication. The QRS axis of E-40 was about 35° at both 500 and 800 pounds and thus far outside the range of the points included in the graph of the S plane data in Figure 7.

QRS Angles: SS Plane: In Figure 7, the QRS angles in the semisagittal plane have also been plotted with 500 pound values on the ordinates and 800 pound values on the abscissae. In agreement with the analysis of variance, there are no obviously apparent weight, sex, or line differences.

The semisagittal plane presents some difficulties in interpretation. Its leads do not form an equilateral triangle, and the heart is not centrally located within it. However, this plane is approximately parallel to the QRS axis of beef and dairy cattle as seen from Spörri's findings and those here related.

It is interesting to note a nonconforming calf in this plane. Female E-5 is not plotted on Figure 7, because its lead III QRS value of —6 yields a QRS angle of 40°, an angle out of range of the graph. In the analysis of the 1956 or "F" series of calves, it was found that this animal's half-brother (same dam) was also a nonconforming calf in its series. This finding suggests that the electrocardiological patterns probably may be, or may contain, inherited characteristics.

QRS Angles: L Plane: The QRS angles in the L plane were so variable from heart beat to heart beat in the same animal that averages were not tabulated in Table 7, but they are plotted in Figure 7. Frequently the QRS angles in the L plane could not be established because of the small magnitude of the projection of the QRS radius vector in the L plane and the lack of consistency in intersection of the perpendiculars. A change in the QRS axis in the S plane from 85° to 95° could induce a 180° change in the L plane.

The scattering of points for the L-plane angles of Figure 7 show one reason why the leg-lead plane by itself has caused bovine electrocardiologists so much trouble. The fact that respiratory movement makes these angles indefinite adds to the difficulty. Note that the 6 animals, labeled indeterminate in the L plane, appear in the area of 90° in the other planes, as one would expect from general theory.

Discussion

The fortuitous occurrence of the human QRS electrical axis in the plane of the limb leads probably helped in the rapid development and wide spread application of electrocardiographic techniques in clinical medicine. There was a great difference between the normal and the grossly abnormal; consequently data were rapidly accumulated. It was the rapid accumulation of data, the occurrence of numerous borderline pathological cases, and the frequency of contradictory observations that eventually led to many new methods, techniques, and theories. Among these the concept of three dimensional or spatial vector electrocardiology and the development of equipment to utilize this concept has probably been the greatest recent improvement in electrocardiology.

The original monoplanic Einthoven triangle was not exactly amenable to interspecies transfer, and many studies in quadrupeds yielded incomplete information. In order to achieve satisfactory utilization of information in bovine electrocardiograms, the concept of spatial vectors must be a basic part of the study. In cattle the spatial concept of electrocardiology is even more necessary than in man because the cardiac electrical axis is usually perpendicular to the plane of the leg leads, and these leads are therefore nearly isoelectric.

Some discussion of the significance of cardiac vectors has been given along with experimental findings in order to avoid duplication. Additional discussion is required for wave forms, cardiac intervals, and the selection of leads.

Wave Forms: Early electrocardiologists were concerned with wave forms, and much literature has been accumulated in descriptions and classifications of these wave forms. However, the advent of vector cardiology and the study of vector loops has shown that these wave forms represent projections of the momentary electrical vectors on the axis of the lead chosen, and thus the form varies with the orientation of the leads toward the momentary cardiac vector. This bulletin emphasizes vector orientation instead of wave forms of the electrocardiogram.

P-Wave: Many authors have dealt considerably on whether the P-wave is notched or not and the percentage of animals which show this condition in the lead system which that author had used. The configuration of the P-wave depends upon the angle from which the record is taken, upon the magnitude of the force generated, as well as upon the site of origin of the electrical force. In general, all unipolar leads taken from the positive side or head of the vector will be positive in deflection. Those on the null band will be isoelectric or zigzagged, while those in the negative area will produce a negative deflection on the EKG.

Sykes and Alfredson (2), using limb leads, showed that a low potassium ration caused interval changes and indicated a marked shift of the electrical axes of the heart. Sykes and Alfredson noted that the increase in the duration of the QRS complex was accompanied by

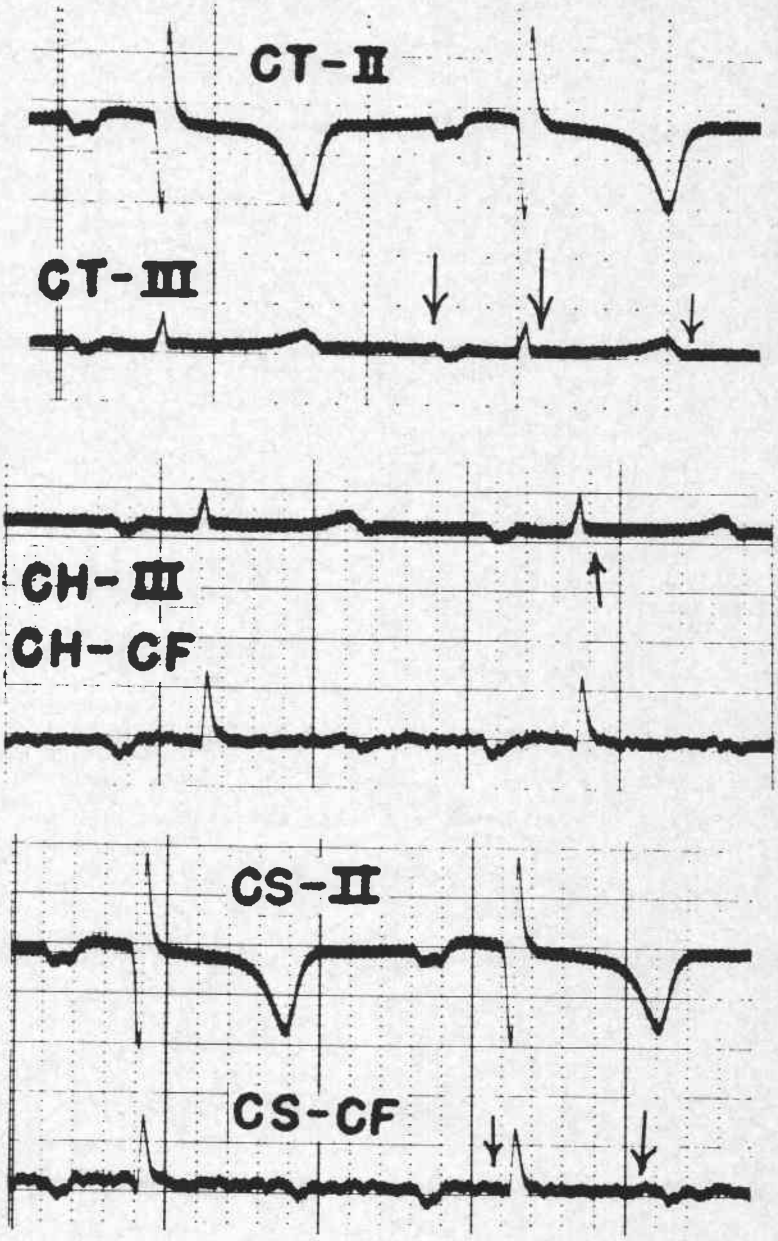


Figure 8. Cube system, Calf 892.

equally striking changes in QRS contour and voltage. Further study is needed to determine the role of a possible shift in the QRS axis.

QRS Complex: Variation in the magnitude of the QRS complex due to the rotation of the heart because of the respiratory cycle may be seen in the human EKG, especially in a stocky individual. In suitable leads this cyclic rotation of the electrical axis may also be demonstrated in beef calves.

Cardiac Intervals: Figure 8 gives simultaneous recordings of the three pairs of electrocardiograms possible with three bipolar leads at right angles to each other (CT-II, CT-III, or CH-CF; leads not previously described but notation of little consequence for the immediate purpose of this discussion). The QRS complex is 0.04 second in lead CT-II, 0.02 in lead CT-III, and 0.03 in lead CH-CF. The early portion of the QRS complex in lead CH-CF and the late portion in lead CT-III are recorded isoelectrically.

Measurements of cardiac intervals are to be compared cautiously because a varying orientation of the QRS, T, and P axes from animal to animal will give rise to apparent differences in cardiac intervals, where none may exist. An isoelectric period in one axis may yield a measurable potential in another. A shift in any electrical axis may induce a change in the time over which a visible displacement from the isoelectric line is observable. Variability in either the QRS or P complex duration would give rise to a variation in the PR interval, and the PR interval is an important diagnostic characteristic in the interpretation of electrocardiograms.

Figure 8 shows that over significant and measurable lengths of time the record may be isoelectric in one lead and yield a measurable potential in another lead (see arrows). A shift in the positions of the anatomical axis of the heart, but with the electrical events in a cardiac cycle otherwise unmodified, would yield shorter complexes in leads moved toward the perpendicular to the axis by the shift, and longer complexes in leads tending to become parallel to the axis. Because of these two important considerations some of the previous work in the field of bovine electrocardiography based upon a monoplaner or a monaxial system may need to be reevaluated.

For cattle it appears that as long as the lead selected includes significant components of the QRS, T, and P axes, the intervals will be reasonably accurate and probably useful under most circumstances. A lead will lose its accuracy for interval measurements whenever one or more of the axes is recorded with a low potential. Because Leads S-II and S-III record major components of the three cardiac electrical axes, these leads have been chosen as being the most suitable for the measurement of intervals in electrocardiograms taken at 500 and 800 pounds body weight.

For comparing cardiac intervals, the ideal situation can be approximated with the aid of a six channel simultaneous recorder and by taking the information from the leads which recorded the initial and the final components for each wave. Because this ideal is not always attainable, the practical procedure is to select the most satisfactory lead available and to make measurements of the PR, QRS, TQ, and QT intervals within a single heart beat.

Selection of Leads in Cattle: One qualification for a single satisfactory lead for comparison between individuals is the presence of identifiable points for the start of the P and QRS complexes and for the end of the QRS and T complexes. For the determination of cardiac intervals, isoelectric recordings or indefinite waves preclude an accurate evaluation. Artefacts induced by muscle tremor interfere with accuracy.

A second qualification includes ease of anatomical identification and ease of electrode placement.

As is pointed out in many textbooks (e. g., Dimond, p. 42), the limbs are linear conductors which transmit peripherally the potentials existing at the regions of their attachment. Therefore, the reproduceability of the limb leads is easily and conveniently accomplished. Variations in electrode placement have a minimum effect. Leads taken from the body wall require exact placement and this is difficult to accomplish on continually moving animals.

According to Table 2, the potentials in the leg leads are quite variable. If one also considers the QRS axis angle values (Figure 7, leg lead plane), it becomes apparent that neither the leg lead QRS potentials nor the QRS axis projection angles are completely reliable indicators of the cardiac electrical properties for calves of 500 and 800 pounds body weight. However, the vector information obtained from the leg leads is necessary for the calculation of three dimensional vector orientation.

The shape of the human body is such that the precordial electrodes are much nearer to the heart than the limb lead electrodes, and the orientation of the heart in the body is such that one may use the precordial leads to identify pathologies in the right and left chamber and the septum (16). It is difficult to apply precordial leads in cattle. In the beef calf the heart is rotated almost 90° from the position in man, and the septum is located transversely. The best precordial positions are covered by the muscular connections of the fore limbs. To this may be added the difficulty of placing the electrode straps in the required position.

The V lead has been placed in almost every conceivable sector of the animal's body but apparently did not get close enough to the heart to give more information than the normal hexaxial system except in a few instances. Furthermore, there was some difficulty in maintaining the position of an electrode in many areas such as the brisket or the rear body wall. Also, the front legs with their large muscle masses were in the way of accurate electrode placement in large and important sectors.

For convenience, electrode positions were selected which could be maintained by a rubber strap around the body just behind the front legs. This band allowed the placement of the exploratory electrode on the right sternal margin at about the 5-6th rib interspace. This was designated as V_1. Location V_2 was midsternal; V_3 on the left sternal margin; V_4 under the olecranon; V_5 at the intersection of a horizontal line from the point of the shoulder; and V_7 near the dorsal angle of the scapulae. A convenient location just ahead of the scapula in the cervical region was designated V_8, and it was secured by straps which went around the animal, but between the front legs. The right side of the body was a mirror of the left side in that V_9 was opposite V_7, and V_{11} opposite V_5.

A study of Figures 1 to 3 indicates that easily identifiable P, QRS, and T complexes are found in only 18 of the 67 leads used. Seventeen of these were dorsally-ventrally oriented, and one (CR_5) was transversely oriented from V_5 to the right forelimb insertion. Most of the leads with the P, QRS, and T complexes identifiable involved either the scapular position, the electrode behind the left olecranon, or the sternal region.

The S-CF leads when connected to the chest positions V_1, V_3, or V_4 are very similar to the leads used by authors who devised the prescapular-heart apex area lead. These can be seen to give good records and excursions of measurable magnitude. In these leads the electrodes lie on or near the cardiac axes of normal animals. In an animal with deviated axes, these leads will no longer be in line with the cardiac axes, and their advantages disappear.

In data compounded from measurements involving the low potential leads I, II, and III (L-Plane), the experimental and statistical error will be much greater than in similar data compounded from measurements involving the higher potential leads S-II and S-III (S-plane). Where relationships involving ratios of potentials are concerned, the ratios from leads I, II, and III will be subject to a greater error of measurement than similar ratios from leads S-II or S-III. Hence the S-plane will be more valuable than the L-plane in comparisons where a minimum error in QRS potential is required.

The QRS potential is generally large and clearly defined in S-II or S-III, while the P-wave and the T-wave are usually well defined in these leads. Since standard deviations and coefficients of variation for potentials are much higher in the leg leads, and since QRS potentials in the leg leads are low, the S plane in our experience has been a more satisfactory plane than the L-plane for the determination of cardiac intervals (QRS durations, PR, TQ, and QT intervals) at body weights of 500 or 800 pounds.

From time to time, leads S-II and S-III are unsatisfactory for cardiac intervals because of difficulty in interpreting start of the P-wave or the end of the T-wave. Leads I, II, or III may then be more easily interpreted. However, it must be remembered that intervals are not identical in all leads, and information from leads S-II and S-III have not been established as directly comparable to data from leads I, II, and III. Furthermore, in young calves, up to two months of age, the leg leads show good potentials while the S potentials are very small.

Before final decisions can be made, extensive comparison of intervals estimated for several leads in a large series of animals are required to determine means, variability, differences, and conditions within and between series of calves. In general, most information for the vector directions of the cardiac axes may be adequately obtained from the L and S-plane leads through geometric means, and the electrical properties of various animals may be compared one with another by means of these two planes.

The selection of the best lead or group of leads for diagnosis or for the measurement of experimental effects must remain up to the individual who is studying the abnormal or experimentally changing EKG records.

X-Plane. An important X-plane hexaxial system can be developed from electrodes placed on V_3, V_7, and V_9. A plane through V_3, V_7, and V_9 gives a vertical cross section of the calf and makes an angle of 15° with the S-Plane. The leads of the X-Plane hexaxial system yield electrocardiographic records clear, sharp, and free from the muscle tremor characteristics of leads from electrodes on the supporting limbs. Since the anatomical placement of the heart is somewhat to the left, the apex of the EKG triangle was also placed to the left (left sternal margin). It can be seen in Figure 6C that in the X-plane the QRS axis and the T axis have almost opposite directions.

Summary

Electrocardiograms taken of beef calf F-25 from 67 distinct leads have been reproduced and their meaning discussed. Basic procedures have been outlined, basic terms have been defined, and the underlying theory has been presented. Analysis of data from calf F-25 form the greater and introductory part of this bulletin. The second portion of the bulletin is concerned with the QRS complexes

of 33 Hereford calves (E series, Oregon State College) born in the year 1955.

In the analysis of electrocardiograms four areas of information are investigated: (1) Wave characteristics, (2) Time intervals, (3) Cardiac potentials, and (4) Data on the axes of electrical activity. Electrocardiograms are made up of the P, the QRS, and the T complexes.

In accordance with a theory proposed by Lewis, as the electrical potential develops in the heart, minute areas of cardiac muscle become electrically negative to adjacent areas and form microscopical dipoles. The dipoles sometimes neutralize and sometimes reinforce one another. At any given instant the innumerable microscopic dipoles are equivalent to a single resultant dipole. The resultant dipole has a magnitude and a direction and is referred to as an axis.

To establish the direction of a cardiac axis, a set of standard anatomical electrode positions is set up to yield ease of application of electrodes, minimum artefacts in the recording, and the choice of six leads whose axes are spaced 60° apart. In each lead will be recorded the potential of the resultant dipole multiplied by the cosine of the angle between the resultant vector and the lead. The axis is determined geometrically by construction from the cosine components.

The QRS vector for calf F-25 may be expressed as $V_{QRS} = -4.0\,\mathbf{i} + 8.1\,\mathbf{j} + 2.4\,\mathbf{k}$. The vector may also be expressed as having an azimuth angle of 60° from the left arm toward the head in the leg lead plane, a 60° angle of elevation, and a radius vector length of 9.3 units or 0.93 millivolts. The vector points dorsad, cephalad, and to the left.

The T vector for calf F-25 may be expressed as $-1.2\,\mathbf{i} - 2.8\,\mathbf{j} -1.5\,\mathbf{k}$. The vector may also be expressed as having an aszimuth angle of 144° from the left arm (rotating from the left arm toward the head and then toward the right arm) in the L plane, an angle of depression of 54° below the L plane, and a radius vector length of 3.4 units or 0.34 millivolts. The T vector points downward, to the right, and cephalad. The QRS and T vectors have an angle of 134° between them.

The P vector for calf F-25 may be expressed as $1.4\,\mathbf{i} - 0.8\,\mathbf{j} + 0.16\mathbf{k}$. The vector may also be expressed as having an azimuth angle of 79° from the left arm (rotating from the left arm toward the tail) in the L plane, an angle of depression of 60° below the L-plane, and a radius vector length of 1.6 units or 0.16 millivolts. The vector points ventrally, caudally, and slightly to the left.

In the E calves there was a greater variability in leg lead potentials recorded from calf to calf than were found in the scapular lead potentials from calf to calf.

Potentials observed at 800 pounds were thus related to the potentials observed at 500 pounds (except in lead III). In general low potentials (algebraically) at 500 pounds were accompanied by low potentials at 800 pounds; and high potentials were associated with high potentials. Potentials in leads I, II, III, and S-I tended to be higher at 500 pounds than at 800 pounds body weight.

Determination of the coordinates of the QRS axis in three dimensional space is difficult to apply for comparisons over extensive series of animals. Instead comparisons usually involve the component projected upon a convenient plane.

Choice of planes to be studied depends on experience, anatomical considerations, and geometrical configurations. As three planes essentially at right angles to one another we have envisioned the *M plane,* the *L plane,* and the *S plane.* The mid-sagittal or M plane is placed through the interscapular space, the dorsal lumbo-sacral border, and the mid region of the sterum. The L plane is placed through the insertions of the right forelimb, left forelimb, and left rear limb. The S plane is placed through the dorsal prescapular region, and the right forelimb and the left forelimb insertions.

Limb leads were chosen partly on analogy with the important limb lead plane in man, and partly because experience indicated that the limb leads, although yielding electrocardiographic complexes difficult to interpret and analyze by themselves, provided valuable information in determining the QRS axis.

It was also found useful to study a fourth plane, the *semisagittal* (SS) *plane* through the prescapular space, the left forelimb and the left hind limb. For many 500-800 pound calves the QRS axis lies in or very near the semisagittal plane and hence maximum potentials are frequently recorded in leads of the semisagittal plane, and a maximum QRS vector component is frequently obtained.

The average QRS angle in the S plane shows little change between 500 and 800 pounds. In the S plane the QRS angle was not significantly different in males and females. However, Prince calves had smaller QRS angles than did the Davids or the Lionhearts. For the S plane the zero degree reference line points to the left, positive angles are upwards and negative angles downward. All QRS angles in the S plane were positive and ranged from 70 to 115° at 500 pounds and from 68 to 115° at 800 pounds. All calves of the Prince line except two had low values (68° to 94°) of the QRS angle in the S plane at both 500 and 800 pounds body weight. However, the other two Prince female calves had QRS angles of 103° to 105°. Both of the calves were chronic bloaters, and one died before attaining 800 pounds body weight.

None of the animals in the David or Lionheart line had QRS angles in the S plane less than 90°, except E 40, a calf which had a series of complex heart anomalies to be described in a separate publication. The QRS axis of E 40 was about 35° at both 500 and 800 pounds.

The QRS angles in the L plane were variable from heart beat to heart beat in the same animal. Frequently the QRS angles in the L plane could not be established because of the small magnitude of the projection of the QRS vector in the L plane.

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