# McFee and Parungao orthogonal lead vectorcardiography in normal dogs

by

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# INTRODUCTION AND OBJECTIVES

Vectorcardiography is a measurement of the direction, magnitude and orientation of the mean instantaneous voltage distributions of the heart. Atrial depolarization, ventricular depolarization and ventricular repolarization are each represented by a single loop, the P loop, QRS loop and T loop respectively. These are the loci of the tips of the positive ends of the infinite number of instantaneous vectors, and are based upon the concept that the heart is a single, fixed equivalent dipole.

Vectorcardiography's acceptance and availability in clinical medicine has been retarded by expense of equipment, operation time required, lack of a standard lead system and unfamiliar biophysical theory. It has the advantage of accurately representing the complete electrical activity of the heart by recording deflections in the three major body planes from orthogonal leads. Vectorcardiography is useful in understanding and teaching the sequence of events in the cardiac cycle, in anticipating qualitatively the appearance of any scalar lead and in providing valuable diagnostic information.

Various lead systems and abnormal vectorcardiographic deflections caused by acquired or congenital cardiac abnormality in the canine have been described qualitatively. Experimentally produced cardiac lesions have been created in dogs as a means of studying cardiovascular disease in man. In some cases, vectorcardiography has been used to monitor the effects of the lesions. However, these reports and investigations have preceded the establishment of normal canine quantitative criteria for a corrected orthogonal lead system.

The purpose of this investigation was to quantitatively and qualitatively describe the normal vectorcardiogram of the canine as recorded from corrected orthogonal leads specifically developed for the dog. The significance of the difference between individuals was statistically analyzed. Day-to-day variation in the placement of electrodes and shifts in the equivalent dipole generator within serial recordings of the same dog were investigated. Variations of vectors' orientation and magnitude between sex were analyzed. Finally, thoracic ratios were correlated with the orientation and magnitude of selected instantaneous vectors.

# LITERATURE EVALUATION

## Evolution of Vectorcardiography

In 1889 Waller[108] established the theory of the cardiac generator acting as a single fixed dipole by immersing limbs of various species in salt solution to measure the electrical activity of the heart. He assumed that the spread of equipotentials radiated from the dipole in a uniform manner as waves in a pool of water. Einthoven[33] in 1903 introduced the more sensitive string galvanometer and developed three standard limb leads for the frontal plane. Subsequently in 1913 Einthoven et al.[34] published their classical method of the determination of the "manifest value" of the heart which is now referred to as the mean electrical axis in the frontal plane. This provided only a two-dimensional concept of the loop of instantaneous vectors and was still based upon the supposition that equipotential lines radiated uniformly from a single fixed equivalent dipole, although they had observed that analogous peaks did not occur in phase.

Mann[71] was the first to construct vector loop figures by manually combining two of the standard leads into a

single curve and called them monocardiograms. Savjaloff[92] later placed several electrodes at various points on the body and obtained the first vectorcardiogram (VCG) in the transverse plane, which enabled him to visualize the constantly changing cardiac potentials in three dimensions. In 1931 Mann[72] plotted the VCG of the frontal plane from standard leads I, II and III and stated that the VCG can be useful in diagnosis of left bundle-branch block and right bundle-branch block. By 1938 Mann[73] had devised a special three-coil galvanometer, which integrated the standard leads into one tracing, and described examples of right ventricular hypertrophy, left ventricular hypertrophy, ventricular conduction defects, right bundle-branch block, left bundle-branch block, experimental coronary artery ligation and extrasystoles. His three-coil galvanometer was quickly outmoded by the oscilloscope. First use of the oscilloscope in electrical cardiac monitoring was done in 1936 by Schellong[94], who used the term vectordiagram. Additional work was done by Hollmann and Hollmann[62], who called the loops a triogramm. Wilson and Johnston[109] also monitored the planar electrical activity of the heart with the aid of the oscilloscope and were the first to suggest the more

descriptive term vectorcardiogram.

Burger and van Milaan[19, 20, 21] mathematically proved, using torso models, that the activity of the heart can be represented as a single instantaneous vector if the electrodes are at a sufficient distance from the heart. Realizing that the spread of surface voltage distributions does not radiate in a uniform manner because of variations in tissue resistivity, body contour and anatomic position of the heart, they attempted to find coefficients which would correct Einthoven's[33] frontal plane triangle.

Burger and van Milaan[19, 20, 21] "lead vector" concept stimulated numerous investigations on the development of new lead systems for the production of a more representative vectorcardiogram. Schellong[94] was the first to abandon the equilateral triangle in favor of the orthogonal placement of bipolar leads, but his electrodes were too near the dipole and resulted in a distorted image. Wilson et al.[110] suggested replacing the Einthoven triangle with a tetrahedral arrangement of the electrodes. Although it was a convenient method, it was not truly orthogonal. Duchosal and Sulzer[32] produced a double cube VCG lead system modification of Schellong's[94] technique by placing

the electrodes more distally. However, the vertical component was twice the distance of the horizontal and depth components. In 1952 Grishman and Scherlis[46] described a cube A, B, C lead system which was based on convenient anatomical and geometric locations as equidistant from the dipole center of the heart (E) as possible, but since the Z lead was fifteen percent shorter or closer to E, a compressed loop resulted.

Vectorcardiographers continued to search for an ideal lead system which would produce more representative loops. Grishman and Scherlis [46] were aware that the dipole center could not be determined in a particular subject, although the results of the lead system depended heavily upon the position of the electrodes in relation to E, the isoelectric point. Frank[42] and Schaffer[93] proved the inadequacy of a geometric lead system on artificial torso models by demonstrating the effects of the varied and high resistance of the lungs, liver and vertebral column, plus the distortion caused by irregular body surfaces and environmental factors.

Subsequently, orthogonal leads and resolvers were incorporated into lead systems to correct the distortions. McFee and Johnston[76, 77, 78], following Burger and van

Milaan's[19, 20, 21] example of the "lead vector" concept, derived their corrected "lead field" theory in 1953 and 1954. They found that by recording a lead with a network of electrodes, rather than only two electrodes, the error caused by multiple dipoles or shifts in a single dipole could be significantly minimized. Schmitt and Simonson[97] described a "stereovectorelectrocardiographic" corrected lead system (SVEC III) in 1955, consisting of fourteen electrodes. This system has proven to be an accurate and commonly used lead. Helm[56] attempted to devise an improved Z lead which incorporated a large square stainless steel foil electrode. Later he experimented with multiple sponge electrodes[55]. Reynolds et al.[87], trying to improve the "field" approach, advocated thin, flexible metal plates on sponge rubber sheets with as many as sixty-three electrodes incorporated in one lead. Frank[39] developed a seven-electrode corrected lead system for man in 1956 which was both simple to use and relatively accurate. It has attained widespread, but not exclusive, acceptance in recent years.

The latest lead system to attain any widespread use was designed by McFee and Parungao[79] in 1961. This "axial" lead system was proclaimed to achieve an optimum

balance between accuracy and simplicity. Based upon the "lead field" theory, the placement of the electrodes was less critical than Frank's[39] lead system, yet was not as complex as the Schmitt and Simonson[97] system.

By 1954 vectorcardiography had become so well accepted that the Committee on Electrocardiography of the American Heart Association[1] tried to standardize terms, leads and specifications for instrumentation in vectorcardiography. These recommendations were improved by Helm[57] in 1956 and adopted by most vectorcardiographers. Consequently, when the Committee was reformed in 1967, Helm's[57] vectorcardiographic notations were incorporated into its latest recommendations[2].

Despite the efforts of the American Heart Association to alleviate the confusion concerning the selection of a universal lead system, new lead systems or modifications of older systems continued to appear in the literature and to attract brief attention. Investigators published normal values for various quantitative criteria using their preferred lead systems. Since no uniform opinion as to the ideal lead system could be agreed upon, Burger et al.[16, 17, 18] attempted to convert values from one lead system to

another by determining the correct mathematical coefficients, but were unsuccessful. Brody and Arzbaecher[11] and Horan et al.[66, 67] also failed to arrive at a transformation equation with the aid of digital computers. Unable to agree upon a universal lead system and unsuccessful in mathematically transposing criteria, investigators proceeded to comparatively evaluate the relative values of the current lead systems.

## Comparison of Lead Systems

Comparison studies followed the introduction of each new lead system. Since corrected systems utilized orthogonal axes with equal lead sensitivities, it was soon apparent they would be more consistent and produce more representative vector loops than the older, noncorrected systems.

Brody and Arzbaecher[11] reviewed the lead systems of Schmitt and Simonson[97], McFee and Parungao[79], Frank[39], Grishman and Scherlis[46], Wilson et al.[110] and McFee and Johnston[76, 77, 78]. Although all systems had a twenty percent error in the usable information, the McFee and Parungao[79] lead had the lowest individual error.

The McFee and Parungao[79] lead system Z axis was

compared with Schmitt and Simonson's[97] and Frank's[39] by Fischmann and Elliot[38] in 1964. Both the Frank[39] and McFee and Parungao[79] Z axis leads were inferior to a simple bipolar lead in uniformity and orthogonality. The Schmitt and Simonson[97] system was relatively uniform.

Fischmann[37] compared the transverse (X) and vertical (Y) lead components of the same systems. It was found that the McFee and Parungao[79] system produced results with low standard deviations. It was the only corrected lead system in the investigation which was originally based on torso model studies and data from living subjects. Duchosal[31], a pioneer in vectorcardiography, adopted the use of the McFee and Parungao[79] system in 1963, being convinced of its greater reliability in routine clinical use as compared to Frank's[39] system.

In 1966 Gamboa[43] influenced by the work of Brody and Arzbaecher[11], investigated the applicability of the McFee and Parungao[79] system in children. It was demonstrated to be clinically orthogonal and uniform with insignificant distortions resulting from the size of the subject.

## Normal Human Vectorcardiograms

Confusion existed not only concerning the selection of

the best lead system, but also concerning differences of opinions on how to evaluate the vectorcardiograms. Despite the lack of a standard lead system, normal values began to be established as soon as vectorcardiography attained wide usage in the early 1950's. At first only qualitative descriptions of the vector loop were reported.

However, it soon became evident that quantitative values would be necessary for accurate diagnosis and computer analysis, In 1954 Simonson and Keyes[99] surveyed 178 normal men and calculated the three-dimensional or polar vector, a process which proved to be tedious and difficult to evaluate clinically. Seiden[98] attempted quantitative evaluation of normal loops obtained by Frank's[39] lead in 1957 by measuring the greatest diameter within the loop, its greatest perpendicular width-to-length measurement and three width-to-length ratios. Pipberger[84] evaluated several methods of data analysis for Schmitt and Simonson's[97] lead VCG. Maximum vector magnitude and orientation ranges were nearly half those obtained by conventional electrocardiogram leads. Length-to-width ratios and 0.01, 0.02, 0.03 and 0.04 second QRS interval vectors were also oriented and measured.

Bristow[10] expanded upon Seiden's[98] investigation of Frank's[39] lead VCG in normal humans in 1961. Maximum vectors were oriented, but were not measured in magnitude. Half-area vectors were plotted by Pipberger's[83] method of planimetry. This measurement resulted in a lower range of distribution in the horizontal and sagittal planes. Frontal plane loops were usually narrow, and half-area vectors were assumed to be the same as maximum vectors. Percentages of the loops' areas in each Cartesian quadrant of the three planes were analyzed.

With the assistance of digital computers, Draper et al.[30] quantitatively evaluated Frank's[39] lead system in 510 normal men. Their criteria included the measurement of maximum vectors, the amplitude and direction of all 0.01 sec. vectors of the QRS loop, the equal one-eighth division vectors and the polar vectors.

Clinically the most practical methods of evaluation appear to be qualitative, such as direction of inscription of the loop and configuration of the total loop. Quantitative values are advantageous in subclinical electrocardiographic phenomena and computer programming. Maximum vectors and half-area vectors are well accepted criteria which can be

visually estimated within five degrees.

## Clinical Application

In most clinical instances, the planar vector loops and their scalar X, Y and Z components contain more diagnostic information of the complete electrical activity of the heart than does the standard human twelve-lead electrocardiogram (ECG) or the standard canine ten-lead ECG[81, 100, 111]. Planar vector loops measured from corrected orthogonal leads accurately approximate an infinite number of instantaneous vectors from which deflections in any axis may be predicted[85, 95, 104]. Scalar electrocardiograms are measurements of positive and negative deflections in only a single axis. Burch[12] pointed out in 1952 that the vector loop contained more detail on one cardiac cycle than did the ECG, particularly if the oscilloscope beam was pulsated to segment the sweep of the vector loop. Pipberger[82] stated that the VCG had numerous advantages, such as reduction of data for computers, decreased range of normal values and the lack of the necessity to switch leads. Scalar X, Y and Z recordings can be useful for determination of arrhythmias, ectopic beats, intervals

and segments.

Because of the high incidence of myocardial infarction in humans, it may be necessary to supplement the VCG with unipolar precordial leads. The most efficient measurements of the electrical activity of a particular portion of the myocardium are deflections recorded between a single positive exploring electrode and a central terminal with the area of injury immediately beneath the exploring electrode. Since six unipolar precordial leads are routinely included in standard electrocardiograms of man, the diagnostic accuracy of the VCG in the detection of anterior and left myocardial infarction has been inferior to the ECG[69].

Vectorcardiography has been accepted by most cardiologists as a useful diagnostic tool, if not superior to the ECG[100]. Benchimol and Lucena[3] have demonstrated the correlation of changes in the VCG of children with congenital heart defects and their associated hemodynamic alterations. The VCG, therefore, can serve as a noninvasive screening procedure to determine the working capacity of the heart[86]. More specifically, the VCG can detect with acceptable accuracy the systolic gradient across the pulmonary valve in pulmonary stenosis[3]. Vectorcardiographic investigations

have established its value and sensitivity in the detection of congenital heart defects[13, 51, 52, 86]; complete and incomplete, right and left bundle-branch blocks[44, 80, 91, 96]; left and right ventricular hypertrophy[27, 75, 88, 106, 107]; superior, inferior and posterior myocardial infarctions[15, 60, 61, 90, 105] and Wolff-Parkinson-White's syndrome[14, 22].

## Vectorcardiography in the Canine

Following human and torso model vectorcardiographic investigations of the early 1950's, publications began to appear on canine vectorcardiography. This was a logical sequela, since the dog is frequently used as an experimental model in cardiovascular research.

Normal vectorcardiographic loops in the dog were first described by Hamlin and Hellerstein[50] in 1956 and by Horan et al.[64] in 1957. Both teams of investigators recorded the loops with Wilson's[110] lead system, and the dogs were anesthetized with pentobarbital sodium. Hamlin and Hellerstein[50] recorded the dogs in right lateral recumbency, while Horan et al.[64] used the supine position. Hamlin and Hellerstein's[50] results were

evaluated more quantitatively than Horan et al.'s[64]. The three major vectors of the QRS loop were measured in magnitude and oriented in each plane. Width-depth ratios were calculated, and the progression of the sweep of the instantaneous QRS vectors described. A similar report of the same investigation was published in 1960 by Hellerstein and Hamlin[54]. Horan et al.[64] only reported the orientation of the maximum mean instantaneous vectors and a description of the QRS loop.

The first corrected lead study in normal dogs was by Cook[25] in 1966. He conducted a study of Frank's[39] lead system in normal, anesthetized dogs. Maximum vectors and half-area vectors were oriented and measured in magnitude. Boineau et al.[5] briefly demonstrated the normal VCG in the dog, recorded with the McFee and Parungao[79] leads. Hill[59] reported using Wilson's et al.[110] and McFee and Parungao's[79] lead systems. The McFee and Parungao[79] system was least affected by changes in foreleg positioning of dogs which were anesthetized and recorded in right lateral recumbency.

Since 1970 two reports of the normal canine VCG have contributed much to veterinary cardiology. Ettinger and

Suter[36] empirically described the QRS loop in normal dogs using the McFee and Parungao[79] lead system in 1970, and Bojrab et al.[9] reported in 1971 the normal, unanesthetized canine VCG as obtained by the Frank[39] lead system. Bojrab et al.[9] tabulated data and performed statistical evaluation on maximum and half-area vectors of the QRS loops from fifteen dogs in supine position recorded on three consecutive days.

Various reports of alterations in the VCG of experimental, congenital and acquired cardiac abnormality in the dog have been published. Wilson's et al.[110] lead system has been utilized to investigate the changes in the VCG caused by experimental occlusion of the left circumflex coronary artery[53, 65], ischemia and necrosis of the myocardium[63, 65], premature systoles[6] and bundle-branch blocks[4]. Clark et al.[23] derived a planar VCG of a congenital imperforate septal defect in a dog from simultaneous leads I, aVF and $V_{10}$. The McFee and Johnston[76, 77, 78] system was utilized by Horan et al.[68] to study the relationship between the position of the interventricular septum and the orientation of the VCG. Grishman and Scherlis'[46] lead has been used to investigate bundle-branch

block[28, 101] and coronary artery occlusion[24]. Frank's[39] lead system has also been utilized in experimental bundle-branch block[101]. Qualitative descriptions on the alteration of the VCG recorded by the McFee and Parungao[79] lead system have been reported in cases of ventricular hypertrophy[5, 36], congenital peritoneopericardial diaphragmatic hernia[8], bundle-branch blocks[7, 36], patent ductus arteriosus[36], tetralogy of Fallot[36] and idiopathic cardiomyopathy[36].

A universal lead system does not exist in canine vectorcardiography. Ideally, the system of choice would be specifically designed for the canine thorax and would be a corrected orthogonal lead system as recommended by the 1967 Committee on Electrocardiography of the American Heart Association[2]. The McFee and Parungao[79] lead system is the only one which fulfills both requirements. Even though many pathological cardiac conditions have been recorded with this lead in dogs, normal quantitative ranges of selected instantaneous vectors must be established and evaluated in order that more efficient analysis can be performed, either manually or by digital computers. This was the purpose of this investigation.

# MATERIALS AND METHODS

## Selection of Subjects and Recording Method

Forty dogs of various breeds from clinical studies and research colonies at Iowa State University, College of Veterinary Medicine, were used for this investigation. Their body weights ranged from 6.4 to 32.2 kilograms, and their ages were estimated to be from 8 months to 5 years. Both males and females were included in the study (Table 1).

The acceptance of any subject as representative of the normal population was dependent on determination of clinical cardiovascular normalcy. This was accomplished by physical examination including general condition and attitude, cardiac and pulmonary auscultation, pulse character and rate, rectal temperature, packed cell volume and direct blood smear for Dirofilaria immitis. Radiographs of the thorax in the dorso-ventral and right lateral recumbency positions at peak inspiration were taken using a film-tube distance of 76 centimeters (cm.). Evaluation was based on selected criteria for enlargement of the silhouette of the cardiac chambers and/or pulmonary vasculature[36, 47, 49, 103]. Standard scalar lead electrocardiograms were taken using leads I, II, III, aVR, aVL, aVF and $V_{10}$ with the subject

in right lateral recumbency. The forelegs and hindlegs were positioned at right angles to the long axis of the body and separated by the person who restrained the dog so that the limbs were not in contact. Electrocardiograms were examined for arrhythmia, conduction disturbance and abnormal voltage potential. Records were made of the rate and rhythm of the heart's electrical activity, along with the duration, form, amplitude and spacing of the bioelectric potentials. The direction of the mean electrical axis of the QRS complex was determined for the frontal plane using the algebraic sum of leads I and III. Criteria for the normal ECG in the canine have been established[29, 36, 48, 58, 70]. Eleven of the dogs initially chosen failed to meet the standards mentioned above (Table 1).

Vectorcardiograms were created using the McFee and Parungao[79] lead system for dogs. Each dog was brought into a quiet room and placed on an insulated table in sternal recumbency. Chemical restraint was not used. An assistant gently restrained the dog when necessary. Eleven platinum alloy electrodes were placed subcutaneously, with little resistance from most dogs. One of the two electrodes constituting the negative pole of the X lead was placed at

the level of the costochondral junction in the fifth intercostal space, and the other approximately 3 cm. craniad to the first. The two electrodes, which constituted the positive X pole, were placed on the left side in an analogous position. The negative electrode on the Y lead was placed on the left side of the neck immediately craniad to the point of the shoulder. The positive Y pole was placed posterior to the stifle on the lateral side of the left hindleg. The negative Z pole consisted of three electrodes, two of which were placed at the sternal junction of the seventh rib, and the third placed cranially in the middle of the sternum. The latter was placed at a distance sufficient to create an equilateral triangle centered immediately ventral to the center of the heart. This resulted in a triangle with a center approximately 3 cm. from each of the vertices, depending on the width of the sternum. The positive Z electrode was placed at the $V_{10}$ position or dorsal to the spine of the seventh thoracic vertebra. The right hindleg was grounded (Figure 1).

## Storage and Reproduction of the QRS Loop

The potentials of the electrodes were averaged when

indicated, using precision resistors (±1 percent). The three differential inputs were amplified by a physiological recorder (Beckman Dynograph R411[1]). The physiological recorder recorded the three (X, Y and Z) leads of electrophysiologic data on curvilinear chart paper and simultaneously fed an output into a magnetic tape recorder[(35)] (Honeywell 5600[2]). The physiological recorder output to the magnetic tape recorder was calibrated so that 1.414 volts would equal 2.5 millivolts (mv.) input. Calibrations and voice identification were recorded prior to each recording for the three orthogonal leads at a tape speed of 1 7/8 inches per second (i.p.s.). The three channels of electrophysiological data were then recorded at 60 i.p.s. Each recording required approximately 100 feet of magnetic tape. The recordings were replayed at a later date at 1 7/8 i.p.s. utilizing a low-pass filter (Krohn-

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[1]Beckmann Instruments, Schiller Park, Illinois.

[2]Honeywell, Chicago, Illinois.

Hite 3202[1]) set at a break frequency of 50 cycles per second and observed on a dual beam oscilloscope (Tektronix Type 502[2]) to select a representative loop. After selection of a representative vector loop with a high signal-to-noise ratio, it was plotted by means of an X-Y recorder (Hewlett-Packard 7004b[3]) which was calibrated for 2 cm./mv. Footage was noted on the magnetic tape corresponding to the loop selected so that all three planes of VCG were recorded utilizing the same cardiac cycle (Figure 2). X (side-to-side, positive to the right) and Y (head-to-tail, positive down) lead channels were connected to the X-Y plotter and recorded simultaneously to produce the frontal plane loop (XY). X and Z (dorsum-to-sternum, positive up) lead channels played simultaneously produced the transverse plane loop (XZ). Y (positive to the right) and Z produced the VCG in the left sagittal plane (XZ) as viewed with the subject in quadruped

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[1]Krohn-Hite, Cambridge, Massachusets.

[2]Tektronix Inc., Portland, Oregon.

[3]Hewlett Packard, St. Paul, Minnesota.

position (Figures 3 and 5-7).

## Evaluation of the QRS Loop

The first fifteen dogs were used to investigate the variation in serial recordings from the same dog. Each dog was recorded on three consecutive days (Tables 2 and 4). The second group of fourteen dogs in combination with the first group's day 1 recordings was used to investigate variation caused by difference in individuals, sex and thoracic conformation (Tables 3 and 5). Thoracic conformation was categorized by width-depth ratios as derived from dorso-ventral and right lateral recumbency radiographs. Width of the thorax was measured in centimeters between the internal surfaces at the greatest curvature of the sixth rib. Depth was measured from the mid-ventral surface of the sixth thoracic vertebra to the mid-dorsal surface of the sixth sternebra (Table 1). X, Y and Z scalar component recordings were analyzed for amplitude, polarity, duration and rhythmicity (Figure 4). Vectorcardiograms were produced from the magnetic tape to form a single P, QRS and T deflection from each recording in the three major body planes, i.e. frontal, transverse and left sagittal (Figure 3). The vector loops were then measured by the angular scale

reference system recommended by the 1967 Committee on Standardization in Electrocardiography of the American Heart Association[2]. Magnitude and angle of the maximum QRS vector in each plane and the half-area QRS vectors in the transverse and left sagittal plane were measured. The maximum vectors were determined by a geometric compass with the isoelectric (E) point of origin as the center of the circle. Half-area vectors were estimated visually, then confirmed by planimetry[9, 83]. Direction of inscription was also recorded (Tables 6 and 7). This resulted in a total of fifty-nine recordings, from which one hundred seventy-seven QRS loops from twenty-nine normal dogs were evaluated.

The data were collected, grouped and coded for computer analysis. Descriptive analysis, analysis of variance, t tests and correlation coefficients were done by the Iowa State University Computation Center.

# RESULTS

## Magnitude and Orientation of Vectors

Tabulated data for the magnitude and orientation of maximum and half-area vectors are given (Tables 1-5). Recordings from the first day's vectorcardiograms taken from fifteen dogs and the single recordings from fourteen dogs were combined and described as a group of twenty-nine separate dogs. Typical planar and scalar recordings are presented (Figures 3 and 4). Each plane is described separately.

Frontal plane QRS loops were measured only for magnitude and orientation of the maximum vector as drawn from point E to the positive end of the maximum instantaneous vector. Half-area loops were assumed to be similar and were not calculated since most frontal plane QRS loops are very narrow. Magnitudes of maximum vectors ranged from 1.45 to 5.15 mv. with a mean of 2.85 mv. and a standard deviation of 0.80 mv. Orientations of maximum vectors ranged from +8 to +100 degrees. The mean was +42 degrees, and the standard deviation was 19 degrees.

Transverse plane QRS loops were evaluated quantitatively by measurement and orientation of the maximum and

half-area vectors. Maximum vectors were between 1.30 and 4.85 mv. in magnitude and -108 and +95 degrees in orientation. The mean magnitude and orientation of maximum vectors was 3.00 mv. and -55 degrees, respectively. Standard deviation for the magnitudes of the maximum vectors was 0.90 mv. and their orientations had a standard deviation of 43 degrees. Half-area vectors were between 1.20 to 4.60 mv. in magnitude, with a mean of 2.74 mv. and a 0.90 mv. standard deviation. Orientations of the half-area vectors ranged from -99 to +48 degrees. The mean orientation was -36 degrees, and the standard deviation was 30 degrees.

Maximum and half-area vectors were also measured in the left sagittal plane. The magnitudes of the maximum vectors were between 1.80 and 4.75 mv. The mean of the maximum vectors was 3.10 mv., and the standard deviation was 0.80 mv. Orientations of the maximum vectors were from +17 to +162 degrees, with a mean of +135 degrees and a standard deviation of 41 degrees. Half-area vectors had a range of 1.00 to 4 75 mv. in magnitude. The mean of the half-area vectors' magnitudes was 2.35 mv., and the standard deviation was 0.95 mv. Half-area vectors were oriented from +59

to +152 degrees. The half-area vectors' mean orientation was +117 degrees, and the standard deviation was 26 degrees.

## Statistical Analysis

Statistical analysis was used to aid in the determination of significant differences in the three planes among the magnitudes and orientations of various individuals, serial recordings, thoracic ratios, and sex.

Results of the analysis of variance among dogs and among recording days are given (Tables 8-10). Significant difference at the 0.01 level existed among dogs in every plane, in magnitude and orientation of both selected instantaneous vectors. Significant difference at the 0.05 level among days occurred in only the left sagittal plane half-area orientation. There was no significant difference in any plane's magnitudes or orientations between sex.

Correlations between the thoracic ratios and the magnitudes and orientations of each of the three planes were investigated. Correlations were significant at the 0.03 level with the frontal plane maximum orientation, at the 0.007 level with the transverse plane maximum orientation, and at the 0.011 level with the transverse plane half-area orientation.

# DISCUSSION

The McFee and Parungao [79] vectorcardiographic lead system has been used on normal dogs by Boineau et al.[5], Hill[59] and Ettinger and Suter[36]. Hill[59] was the only investigator to report quantitative values for selected instantaneous vectors. The purpose of his study was to present the significance of foreleg positioning during recordings of the ECG and VCG. Criteria used to evaluate the significance included direction of inscription, orientation of maximum QRS vectors and length-to-width loop ratios. Five anesthetized dogs were recorded in right lateral recumbency with the forelegs in three different positions. QRS loops were viewed in the frontal plane from the ventral aspect, in the transverse plane from the cranial aspect and in the left sagittal plane from a subject in quadruped position.

Hill's[59] orientation of maximum vectors was measured from +X as 0 degrees in the frontal plane, +X as 0 degrees in the transverse plane and +Y as 0 degrees in the left sagittal plane. The range of possible orientations was from 0 to $\pm$180 degrees in each of the three planes. The range of orientations in five dogs recorded in three foreleg

positions was +5 to +120 degrees in the frontal plane, -54 to +121 degrees in the transverse plane and -94 to +75 degrees in the left sagittal plane.

The orientation ranges reported by Hill[59] were compared with data in the present investigation. In the frontal plane Hill[59] had a range of 115 degrees, whereas the twenty-nine dogs in this study had a range of 92 degrees. Transverse plane orientations were within a 181 degree range in the Hill[59] study and within a 203 degree range in this investigation. Orientations of left sagittal maximum vectors in the Hill[59] study were within 169 degrees, compared with a 179 degree range in the present study. Determination of the degree orientation in this study was based upon recommendations of the 1967 Committee on Standardization in Electrocardiography of the American Heart Association[2], with +Z as 0 degrees. Therefore, range of orientations in the left sagittal plane was 90 degrees out of phase compared with the Hill[59] selection of +Y as 0 degrees.

In the present investigation inscription of the frontal plane vectorcardiograms often varied in direction between dogs and within several recordings of the same subject

(Tables 6 and 7). Fifteen of the vectors were inscribed in figure-8 configuration. Eleven were inscribed clockwise, and thirty-four were inscribed counterclockwise. Direction of inscription changed within at least one of the recordings in seven of the fifteen dogs recorded on three consecutive days. Of fifty-nine transverse plane recordings, clockwise inscription patterns were observed only in dog #33. Dog #19 produced three consecutive figure-8 patterns in the left sagittal plane. All other transverse plane and left sagittal plane inscriptions were counterclockwise.

Hill[59] reported on the direction of inscription in vectorcardiograms using the McFee and Parungao[79] lead. Fifteen frontal plane QRS loops from five dogs in three different foreleg positions resulted in clockwise inscriptions in two loops, figure-8 inscriptions in three loops and counterclockwise inscription in ten loops. Three transverse plane QRS loops were inscribed in a figure-8 pattern, and twelve were counterclockwise. All sagittal QRS loops were inscribed in a counterclockwise direction.

In general the initial direction of the progression of the QRS loops was ventrad, caudad and to the left of point E. The vectors gradually changed to a dorsal direction,

then dextrad and craniad. Most P loops were usually too small to measure accurately, since the largest loop's maximum vector magnitude was less than 0.35 mv. in any plane. It was usually directed caudally and left of the midline in the frontal plane, left and dorsal or ventrad in the transverse plane and dorsal or ventrad and caudad in the left sagittal plane. The largest T loop had a maximum vector of 1.3 mv. Its orientation in the frontal plane was caudad and either right or left. Left sagittal plane T loops were ventrad and caudad. Ettinger and Suter[36] have described similar progression of the instantaneous vectors.

Variations between subjects were statistically significant at the 0.01 level for both magnitude and orientation in all three planes. Possible contributing factors include altered ventricular depolarization pathways, conformation, sex, environment, placement of electrodes, positioning of the subject's body, age, position of the heart within the thorax, packed cell volume and tissue resistance[26, 40, 41, 45, 48, 89]. Environment during the recordings and placement of the electrodes were standardized as much

as possible during the present study. Positioning of the subject's body during recordings was standardized within the limits of tolerance in unanesthetized dogs. Age differences were minimized by limiting the selection of subjects to an eight-month to five-year range. Effect of packed cell volume was limited by selection of dogs whose packed cell volume was between 37 and 50 percent. Position of the heart within the thorax, tissue resistance and ventricular depolarization pathways were uncontrolled variables.

Several investigators[26, 40, 41, 45, 48] have described the effect of conformation on the ECG and the VCG, especially the effect of thoracic shape. Gonin[45] has reported that the mean electric axis in the frontal plane is usually more ventral and constant in narrow-chested dogs, such as collies, French poodles, and German shepherds. Broad-chested dogs, such as cocker spaniels and boxers, were reported to have horizontal and more variable axes. Having a vertical axis, the broad-chested dachshund appeared to be an exception. In this study correlation coefficients were calculated between thoracic ratio and the magnitudes and orientations of the maximum and half-area vectors for each plane.

Correlation of the thoracic ratio and the frontal plane maximum orientation was significant at the 0.03 level. Thoracic ratio and transverse plane maximum orientation and half-area orientation were significant at the 0.007 level and 0.011 level, respectively.

McCall et al.[74] and Sotobata et al.[102] have reported significant differences between vectorcardiograms from human males and females. Crawley and Swenson [26] did not find any differences between electrocardiograms from canine males and females. There were no significant differences in the present study between male and female magnitudes and orientations of either maximum or half-area vectors in any plane, as determined by the t test.

Shifts in the dipole and variations in placement of electrodes could produce variation in serial vectorcardiograms within the same individual. However, analysis of variance among days on magnitudes and orientations of maximum and half-area vectors in the three planes was not significant except at the 0.05 level in the left sagittal half-area orientations in this investigation.

The relative superiority of maximum and half-area vectors as quantitative criteria is dependent upon the

configuration of the QRS loop. Loops which are round or have nearly equal initial, middle and/or terminal vectors are more susceptible to variation in orientation of maximum vectors. Narrow loops need to vary little to cause a large, visually detectable change in orientations and magnitudes of half-area vectors. However, half-area vectors had a lower range and standard deviation in the transverse and left sagittal planes. Therefore, excluding very narrow loops, the half-area vector would be a better criterion for evaluation of the loops.

# SUMMARY AND CONCLUSIONS

The McFee and Parungao[79] corrected lead system vectorcardiogram in twenty-nine dogs was described qualitatively, and selected instantaneous vectors were described quantitatively. Planar vectorcardiograms were produced and evaluated in the three major body planes.

Statistically significant differences existed among dogs in magnitudes and orientations of maximum and half-area vectors for the three planes. Statistically significant differences among recordings from fifteen dogs on three consecutive days occurred only in the left sagittal plane half-area orientations. No statistically significant difference was found between sexes. Thoracic conformation was significantly correlated with orientations of frontal plane maximum vectors and with orientations of transverse plane maximum and half-area vectors.

Direction of inscription of the QRS loop in the frontal plane was usually counterclockwise, but figure-8 and clockwise patterns occurred frequently. In the transverse plane, loops were counterclockwise except for one clockwise inscription. One of the twenty-nine dogs produced three consecutive figure-8 patterns in the left

sagittal plane. All other loops were inscribed counter-clockwise. Both exceptions were marginal situations. The clockwise transverse plane loop was extremely narrow and the figure-8 loops were only effected in the terminal one-fifth of the QRS loops. Most clockwise transverse and left sagittal plane inscriptions should be considered abnormal.

This evaluation of the McFee and Parungao[79] vector-cardiographic lead system in dogs is inconclusive. Statistically significant variation among dogs does not render the system undesirable. Since it is the only corrected, orthogonal vectorcardiographic lead designed for the dog, it is the best available method of measuring the complete electrical activity of the heart. Although the QRS loop varies significantly among dogs it does not change significantly from day to day in the same dog. Variations among individuals could be reduced by the selection of appropriate instantaneous vectors for loop evaluation depending upon configuration of the loop. Orientations of half-area vectors had lower ranges and standard deviations in the transverse and left sagittal plane. So generally it would be a superior criterion. More narrow loops are best

evaluated by measurement and orientation of the maximum vector. In order to adequately judge the usefulness of this method it is necessary to determine to what extent abnormal loop values coincide with the normal ranges.

Computer analysis of magnetic tape recordings for the X, Y, and Z axes would facilitate the collection and evaluation of more dogs. By using the three corrected scalar VCG leads as opposed to the ten ECG leads, computer analysis and diagnosis could be simplified thereby providing a practical, more accurate method of evaluating the electrical activity of the dog's heart.

# LITERATURE CITED

1. American Heart Association. Committee on Electrocardiography. Recommendations for standardization of electrocardiographic and vectorcardiographic leads. Circulation 10: 564-573. 1954.

2. American Heart Association. Committee on Electrocardiography. Recommendations for standardization of leads and specifications for instruments in electrocardiography and vectorcardiography. Circulation 35: 583-602. 1967.

3. Benchimol, A. and Lucena, E. G. Vectorcardiography in congenital heart disease with the use of the Frank system. Brit. Heart J. 27: 236-250. 1965.

4. Blake, D. G. and Kezdi, P. Vectorcardiography in uncomplicated canine bundle-branch block. Circulation 24: 888-889. 1961.

5. Boineau, J. P., Hill, J. D., Spach, M. S. and Moore, E. N. Basis of the electrocardiogram in right ventricular hypertrophy. Am. Heart J. 76: 605-627. 1968.

6. Boineau, J. P., Spach, M. S. and Harris, J. S. Study of premature systoles of the canine heart by means of the spatial vectorcardiogram. Am. Heart J. 60: 924-935. 1960.

7. Bolton, G. R. and Ettinger, S. J. Right bundle-branch block in the dog. J.A.V.M.A. 160: 1104-1119. 1972.

8. Bolton, G. R., Ettinger, S. and Roush, J. C. Congenital peritoneopericardial diaphragmatic hernia in a dog. J.A.V.M.A. 155: 723-730. 1969.

9. Bojrab, M. J., Breazile, J. E. and Morrison, R. D. Vectorcardiography in normal dogs using the Frank lead system. Am. J. Vet. Res. 32: 925-934. 1971.

10. Bristow, J. D. A study of the normal Frank vectorcardiogram. Am. Heart J. 61: 242-249. 1961.

11. Brody, D. A. and Arzbaecher, R. C. A comparative analysis of several corrected vectorcardiographic leads. Circulation 29: 533-545. 1964.

12. Burch, G. E. Vectorcardiography. Arch. Int. Med. 90: 137-140. 1952.

13. Burch, G. E. and DePasquale, N. The electrocardiogram, spatial vectorcardiogram and ventricular gradient in congenital ventricular septal defect. Am. Heart J. 60: 195-211. 1960.

14. Burch, G. E. and DePasquale, N. P. Electrocardiographic and vectorcardiographic detection of heart disease in the presence of the pre-excitation syndrome (Wolff-Parkinson-White syndrome). Am. Intern. Med. 54: 387-404. 1967.

15. Burch, G. E., Horan, L., Abildskov, J. A. and Cronvich, J. A. A study of the spatial vectorcardiogram in subjects with posterior myocardial infarction. Circulation 12: 418-425. 1955.

16. Burger, H. C., van Brummeler, A. G. W. and van Herpen, G. Heart-vector and leads. Am. Heart J. 61: 317-323. 1961.

17. Burger, H. C., van Brummeler, A. G. W. and van Herpen, G. Compromise in vectorcardiography. I. Displacement of electrodes as a means of adapting one lead system to another. Am. Heart J. 62: 398-400. 1961.

18. Burger, H. C., van Brummeler, A. G. W. and van Herpen, G. Compromise in vectorcardiography. II. Alternation of coefficients as a means of adapting one lead system to another. Am. Heart J. 64: 666-678. 1962.

19. Burger, H. C. and van Milaan, J. B. Heart-vector and leads. I. Brit. Heart J. 8: 157-160. 1946.

20. Burger, H. C. and van Milaan, J. B. Heart-vector and leads. II. Brit. Heart J. 9: 154-160. 1947.

21. Burger, H. C. and van Milaan, J. B. Heart-vector and leads. III. Brit. Heart J. 10: 229-233. 1948.

22. Chung, K. Y., Walsh, T. J. and Massie, E. Wolff-Parkinson-White syndrome. Am. Heart J. 69: 116-133. 1965.

23. Clark, D. R., Anderson, J. G. and Patterson, C. Imperforate cardiac septal defect in a dog. J.A.V.M.A. 156: 1020-1025. 1970.

24. Conrad, F. E. and Taylor, W. J. Vectorcardiographic demonstration of terminal QRS changes in dogs with myocardial infarctions produced by selective coronary artery occlusion. Circulation 26: 701. 1962.

25. Cook, J. K. A study of the Frank vectorcardiogram in dogs. Unpublished M.S. thesis. Library, Oklahoma State University, Stillwater, Okla. 1966.

26. Crawley, G. J. and Swenson, M. J. The canine electrocardiogram prior to and following production of cardiac lesions. Vet. Med./Small Animal Clinician 61: 363-372. 1966.

27. Cueto, J., Tashima, H., Armijo, G., Tuna, N. and Lillehei, C. W. Vectorcardiographic studies in acquired valvular disease with reference to the diagnosis of right ventricular hypertrophy. Circulation 33: 588-598. 1966.

28. de Micheli, A., Medrano, G. A. and Sodi-Pallares, D. Vectorcardiographic study of bundle-branch block on the dog in the light of the process of ventricular activation. Acta Cardiol. 18: 483-514. 1963.

29. Detweiler, D. K. and Patterson, D. F. The prevalence and types of cardiovascular disease in dogs. Ann. N. Y. Acad. Sci. 127: 481-516. 1965.

30. Draper, H. W., Peffer, C. J., Stallmann, F. W., Littmann, D. and Pipberger, H. V. The corrected orthogonal electrocardiogram and vectorcardiogram in 510 normal men. Frank lead system. Circulation 30: 853-863. 1964.

31. Duchosal, P. W. Practical remarks on the McFee and Parungao VCG lead system. Am. Heart J. 72: 287-288. 1966.

32. Duchosal, P. W. and Sulzer, R. La vectorcardiographie. S. Karger, Basle. 1949.

33. Einthoven, W. Die galvanometrische Registrierung des menschlichen Elektrokardiogramm, zugleich eine Beurtheilung der Anwendung des Capillar-Elektrometers in der Physiologie. Pflüger's Arch. f. d. ges. Physiol. 99: 472-480. 1903. Reprinted in Willus, F. A. and Keys, T. E.: Classics of cardiology. Vol. II: 722-728. Dover Pub. Inc., New York. 1941.

34. Einthoven, W., Fahr, G. and de Waarf, A. Ueber die Richtung und die manifeste Groesse der Potentialschwankungen in menschlichen Herzen ueber den Einfluss der Herzlage die Form der Elektrokardiogramms. Arch. ges. Physiol. 150: 275. 1913. Reprinted in Am. Heart J. 40: 163-193. 1950.

35. Estes, E. H., Jr., McCall, B. and Wallace, A. G. Time expansion in vectorcardiography: The advantages of magnetic tape recording. Am. Heart J. 63: 98-100. 1962.

36. Ettinger, S. and Suter, P. F. Canine cardiology. W. B. Saunders Company, Philadelphia. 1970.

37. Fischmann, E. J. Experimental comparison of "parallel grid leads" with simple bipolar, and the SVEC-III, Frank, and McFee-Parungao systems. Am. Heart J. 70: 627-637. 1965.

38. Fischmann, E. J. and Elliot, F. J. Experimental comparison of "parallel grid leads" with simple bipolar, and the SVEC-III, Frank, and McFee-Parungao systems. I. Sagittal leads. Am. Heart J. 67: 792-803. 1964.

39. Frank, E. An accurate clinically practical system for spatial vectorcardiography. Circulation 13: 737-749. 1956.

40. Frank, E. and Kay, C. F. Frontal plane studies of homogeneous torso models. Circulation 9: 724-740. 1954.

41. Frank, E. Determination of the electrical center of ventricular depolarization in the human heart. Am. Heart J. 49: 670-692. 1955.

42. Frank, E. The image surface of a homogeneous torso. Am. Heart J. 47: 757-768. 1954.

43. Gamboa, R. Applicability of the axial lead system to infants and children. Am. J. Cardiol. 18: 690-697. 1966.

44. Gardberg, M. and Roson, I. L. The electrocardiogram and vectorcardiogram in various degrees of left bundle-branch block. Am. J. Cardiol. 1: 592-596. 1958.

45. Gonin, P. Über die lage der elektrischen herzachse beim hund, Inaug. Diss., Bern. 1962.

46. Grishman, A. and Scherlis, L. Spatial vectorcardiography. W. B. Saunders Company, Philadelphia. 1952.

47. Hamlin, R. L. Analysis of the cardiac silhouette in dorsoventral radiographs from dogs with heart disease. J.A.V.M.A. 153: 1446-1460. 1968.

48. Hamlin, R. L. Electrocardiographic detection of ventricular enlargement in the dog. J.A.V.M.A. 153: 1461-1469. 1968.

49. Hamlin, R. L. Radiographic anatomy of the heart and great vessels in healthy living dogs. J.A.V.M.A. 136: 265-273. 1960.

50. Hamlin, R. L. and Hellerstein, H. K. Studies in differential vectorcardiography in the dog. I. QRS vectorcardiogram of the normal dog. Circulation 14: 948-949. 1956.

51. Hasegawa, T., Ito, K., Furuse, A. and Saigusa, M. Vectorcardiogram in cyanotic heart disease (Frank system). I. Tetralogy of Fallot. Jap. Heart J. 8: 181-195. 1967.

52. Hasegawa, T., Ito, K., Furuse, A. and Saigusa, M. Vectorcardiogram in cyanotic heart disease (Frank system). II. Other malformations than tetralogy of Fallot. Jap. Heart J. 8: 264-275. 1967.

53. Hellerstein, H. K. and Hamlin, R. L. Studies in differential vectorcardiography of the dog. II. Early changes in the QRS vectorcardiogram and electrocardiogram following experimental left circumflex coronary artery occlusion. Circulation 14: 953. 1956.

54. Hellerstein, H. K. and Hamlin, R. L. QRS component of the spatial vectorcardiogram and of the spatial magnitude and velocity electrocardiograms of the normal dog. Am. J. Cardiol. 6: 1049-1061. 1960.

55. Helm, R. A. An accurate lead system for spatial vectorcardiography. Am. Heart J. 53: 415-424. 1957.

56. Helm, R. A. The lead vectors of multiple dipoles located on an electrically homogenous circular lamina. Am. Heart J. 50: 883-900. 1955.

57. Helm, R. A. Vectorcardiographic notation. Circulation 13: 581-585. 1956.

58. Hill, J. D. The electrocardiogram in dogs with standardized body and limb positions. J. Electrocardiology 1: 175-182. 1968.

59. Hill, J. D. The significance of foreleg positions in the interpretation of electrocardiograms and vectorcardiograms from research animals. Am. Heart J. 75: 518-527. 1968.

60. Hoffman, I., Taymor, R. C. and Gootnick, A. Vectorcardiographic residua of inferior infarction. Seventy-eight cases studies with the Frank system. Circulation 29: 562-576. 1964.

61. Hoffman, I., Taymor, R. C., Morris, M. H. and Kittell, I. Quantitative criteria for the diagnosis of dorsal infarction using the Frank vectorcardiogram. Am. Heart J. 70: 295-304. 1965.

62. Hollmann, W. and Hollmann, H. E. Neue elektrokardiographische Untersuchungsmethode. Ztschr. f. Kreislaufforsch. 29: 546-558. 1937.

63. Horan, L., Burch, G. E. and Cronvich, J. A. A study of the influence upon the spatial vectorcardiogram of localized destruction of the myocardium of the dog. Am. Heart J. 53: 74-90. 1957.

64. Horan, L., Burch, G. E. and Cronvich, J. A. Spatial vectorcardiograms in normal dogs. Circulation Res. 5: 133-136. 1957.

65. Horan, L., Burch, G. E. and Cronvich, J. A. Spatial vectorcardiograms in dogs with chronic localized myocardial lesions. J. Appl. Physiol. 15: 624-628. 1960.

66. Horan, L., Flowers, N. C. and Brody, D. A. The interchangeability of vectorcardiographic systems. Am. Heart J. 70: 365-376. 1965.

67. Horan, L., Flowers, N. C. and Brody, D. A. The limits of information in the vectorcardiogram: Comparative resynthesis of body surface potentials with different lead systems. Am. Heart J. 68: 362-369. 1964.

68. Horan, L., Hansen, F. L. and Bosquet, R. M. Relationship between the anatomical orientation of the interventricular septum and the manifest orientation of the ventricular depolarization in dogs. Circulation Res. 10: 859-869. 1962.

69. Johnston, F. D. The clinical value of vectorcardiography. Circulation 23: 297-303. 1961.

70. Lannek, N. A clinical and experimental study on the electrocardiogram in dogs. Diss. Med. Clinic Roy. Vet. Coll. Stockholm: 1-189. 1949.

71. Mann, H. A method of analyzing the electrocardiogram. Arch. Int. Med. 25: 283-294. 1920.

72. Mann, H. Interpretation of bundle-branch block by means of the monocardiogram. Am. Heart J. 6: 447-457. 1931.

73. Mann, H. The monocardiogram. Am. Heart J. 15: 681-699. 1938.

74. McCall, B. W., Wallace, A. G. and Estes, E. H., Jr. Characteristics of the normal vectorcardiogram recorded with the Frank lead system. Am. J. Cardiol. 10: 514-524. 1962.

75. McCaughan, D., Koroxenidis, G. T., Hopff, L. G. and Williams, C. New vectorcardiographic criteria for the diagnosis of acquired right ventricular hypertrophy: Comparison with standard electrocardiographic criteria. Circulation 28: 766. 1963.

76. McFee, R. and Johnston, F. D. Electrocardiographic leads. I. Introduction. Circulation 8: 554-568. 1953.

77. McFee, R. and Johnston, F. D. Electrocardiographic leads. II. Analysis. Circulation 9: 255-266. 1954.

78. McFee, R. and Johnston, F. D. Electrocardiographic leads. III. Synthesis. Circulation 9: 868-880. 1954.

79. McFee, R. and Parungao, A. An orthogonal lead system for clinical electrocardiography. Am. Heart J. 62: 93-100. 1961.

80. Neuman, J., Blackaller, J., Tobin, J. R., Szanto, P. B. and Gunnar, R. M. The spatial vectorcardiogram in left bundle-branch block. Am. J. Cardiol. 16: 352-358. 1965.

81. Okada, R. H. A critical review of vector electrocardiography. I.E.E.E. Trans. Biomed. Electr. 10: 95-98. 1963.

82. Pipberger, H. V. Current status and persistent problems of electrode placement and lead systems for vectorcardiography and electrocardiography. Prog. Cardiovas. Dis. 2: 248-262. 1959.

83. Pipberger, H. V. Evaluation of quantitative methods for obtaining mean spatial QRS vectors. Circulation 16: 926-927. 1957.

84. Pipberger, H. V. The normal orthogonal electrocardiogram and vectorcardiogram with a critique of some commonly used analytic criteria. Circulation 17: 1102-1111. 1958.

85. Pipberger, H. V., Bialek, S. M., Perloff, J. K. and Schnaper, H. W. Correlation of clinical information in the standard 12-lead ECG and in a corrected orthogonal 3-lead ECG. Am. Heart J. 61: 34-43. 1961.

86. Restieaux, N. J., Ellison, R. C., Albers, W. H. and Nadas, A. S. The Frank electrocardiogram in complete transposition of the great arteries: Its use in assessment of left ventricular pressure. Am. Heart J. 83: 219-231. 1972.

87. Reynolds, E. W., Cordes, J. F., Willis, P. W. and Johnston, F. D. The use of the lead field concept in the development of leads satisfactory for vectorcardiography. I. The sagittal lead. Circulation 14: 48-54. 1956.

88. Romhilt, D. W., Greenfield, J. C. and Estes, E. H. Vectorcardiographic diagnosis of left ventricular hypertrophy. Circulation 37: 15-19. 1968.

89. Rosenthal, A., Restieaux, N. J. and Feig, S. A. Influence of acute variations in hemocrit on the QRS complex of the Frank electrocardiogram. Circulation 44: 456-465. 1971.

90. Rothfeld, E. L., Bernstein, E., Wachtell, F. W. and Karlen, W. S. The vectorcardiogram in direct posterior wall myocardial infarction. Am. J. Cardiol. 7: 496-504. 1961.

91. Sanchez, C., Walsh, T. J. and Massie, E. The vectorcardiogram in incomplete left bundle-branch block. Am. J. Cardiol. 7: 629-637. 1961.

92. Savjaloff, F. Methode der stereometrischen Electrokardiographie. Ztschr. Kreislaufforsch. 21: 705-716. 1929.

93. Schaffer, A. I. The body as a volume conductor in electrocardiography. Am. Heart J. 51: 588-608. 1956.

94. Schellong, F. Electrokardiographische Diagnostik der Herzmuskelerkrankungen. Verhandl. d. deutch. Gesellsch. f. inn Med. 48: 288-310. 1936.

95. Scher, A. M., Young, A. C. and Meredith, W. M. Factor analysis of the electrocardiogram: A test of electrocardiographic theory. Normal hearts. Circulation Res. 8: 519-526. 1960.

96. Scherlis, L. and Lee, Y. C. Transient right bundle-branch block. An electrocardiographic and vector-cardiographic study. Am. J. Cardiol. 11: 173-186. 1963.

97. Schmitt, O. H. and Simonson, E. The present status of vectorcardiography. A.M.A. Arch. Int. Med. 96: 574-590. 1955.

98. Seiden, G. E. The normal QRS loop observed three dimensionally obtained with the Frank precordial system. Circulation 16: 582-585. 1957.

99. Simonson, E. and Keys, A. The spatial QRS and T vector in 178 normal middle-aged men. Circulation 9: 105-114. 1954.

100. Simonson, E., Tuna, N., Okamota, N. and Toshima, H. Diagnostic accuracy of the vectorcardiogram and electrocardiogram. A comparative study. Am. J. Cardiol. 17: 829-878. 1966.

101. Sodi-Pallares, D., Bisteni, A., Testelli, M. R. and Medrano, G. A. Ventricular activation and the vector-cardiogram in bundle-branch block. Clinical and experimental studies with a critical appraisal of the vectorcardiographic methods of Frank and Grishman. Circulation Res. 9: 1098-1108. 1961.

102. Sotobata, I., Richman, H. and Simonson, E. Sex differences in the vectorcardiogram. Circulation 37: 438-448. 1968.

103. Suter, P. F. and Lord, P. F. A critical evaluation of the radiographic findings in canine cardiovascular diseases. J.A.V.M.A. 158: 358-371. 1971.

104. Toole, J. G., von der Groeben, J. and Spivack, A. P. The calculated temperospatial heart vector in proved isolated left ventricular overwork. Am. Heart J. 63: 539-544. 1962.

105. Toutouzas, P., Hubner, R., Sainani, G. and Shillingford, J. Value of vectorcardiogram in diagnosis of posterior and inferior myocardial infarctions. Brit. Heart J. 31: 629-635. 1969.

106. Upshaw, C. B. Simplified clinically applicable vectorcardiographic diagnosis of left ventricular hypertrophy. Frank lead system. Am. Heart J. 74: 749-756. 1967.

107. Varriale, P., Alfenito, J. C. and Kennedy, R. J. The vectorcardiogram of left ventricular hypertrophy. Analysis and criteria (Frank lead system). Circulation 33: 569-576. 1966.

108. Waller, A. D. On the electromotive changes connected with the beat of the mammalian heart and of the human heart in particular. Trans. Roy. Soc. London 180 B: 169-194. 1889.

109. Wilson, F. N. and Johnston, F. D. The vectorcardiogram. Am. Heart J. 16: 14-28. 1938.

110. Wilson, F. N., Johnston, F. D. and Kossmann, C. E. The substitution of a tetrahedron for the Einthoven triangle. Am. Heart J. 33: 594-603. 1947.

111. Wolff, L., Wolff, R., Samartzis, M. D., Mazzoleni, A., Soffe, A. M., Reinor, L. and Matsuoka, S. Vectorcardiographic diagnosis. A correlation with autopsy findings in 167 cases. Circulation 23: 861-880. 1961.

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# APPENDIX

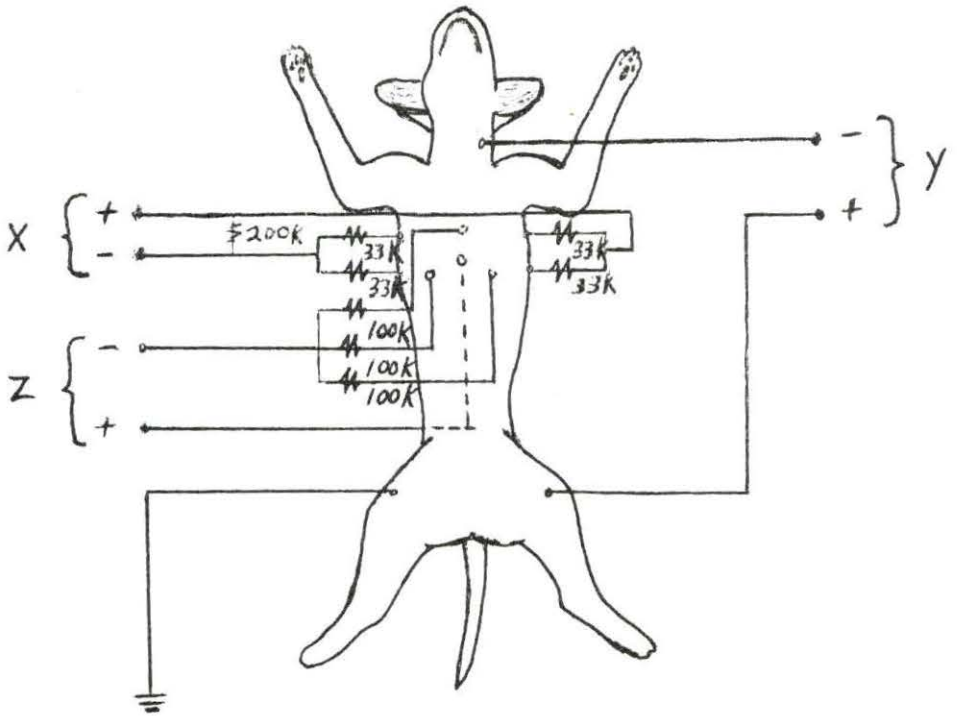


Figure 1. Placement of the McFee and Parungao transverse (X), longitudinal (Y), and sagittal (Z) axis leads as viewed from the ventral aspect of the dog.

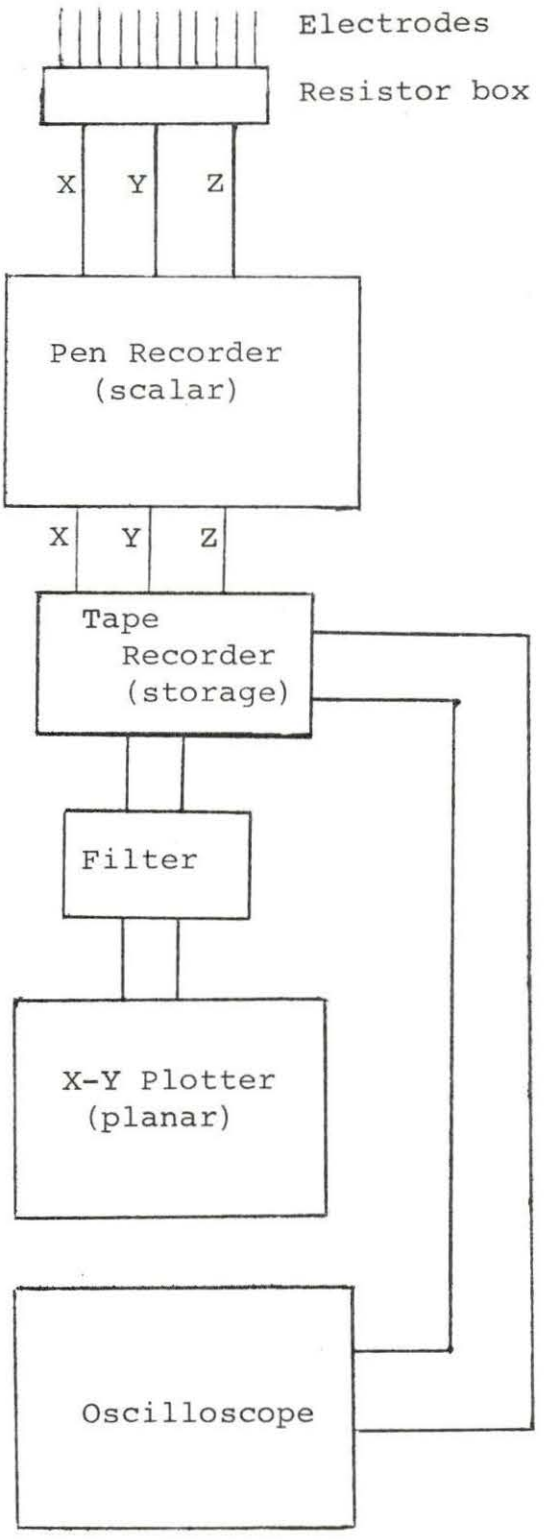


Figure 2. Box diagram for recording and storage of scalar and planar vectorcardiography.

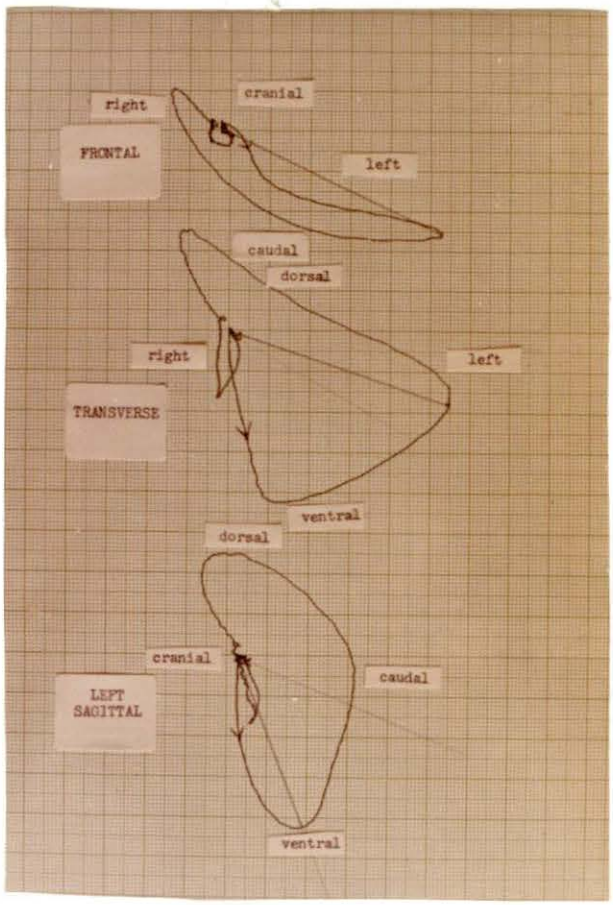


Figure 3. Representative planar vectorcardiogram from dog #39 in the three major body planes.

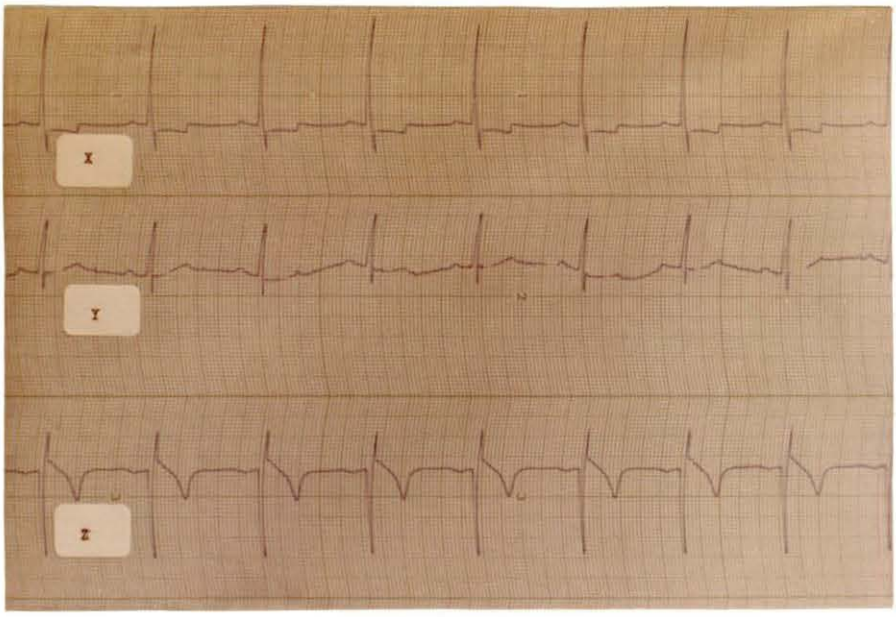


Figure 4. Representative scalar X, Y, and Z components from dog #39.

Figures 5-7. Scattergrams of maximum QRS vectors in the frontal, transverse, and left sagittal planes from fifty-nine separate recordings

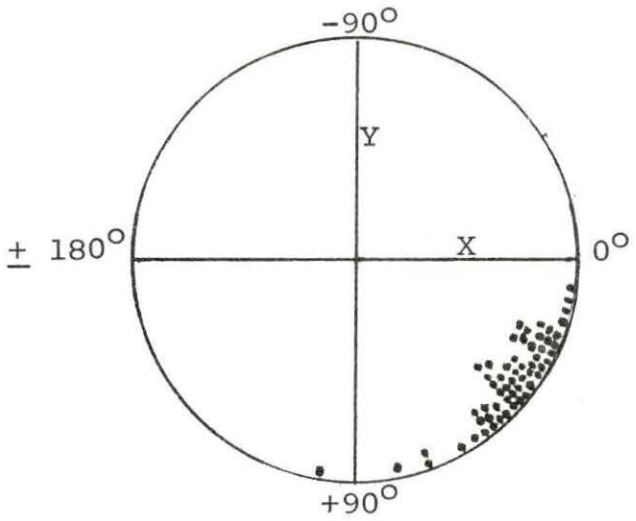


Figure 5. Frontal plane

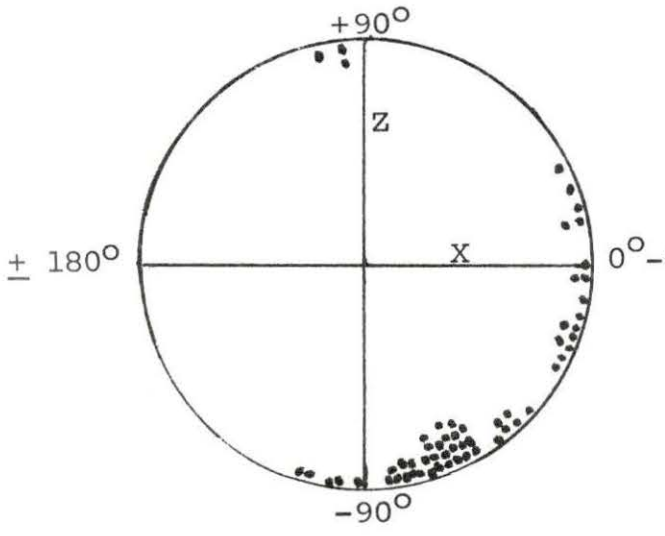


Figure 6. Transverse plane

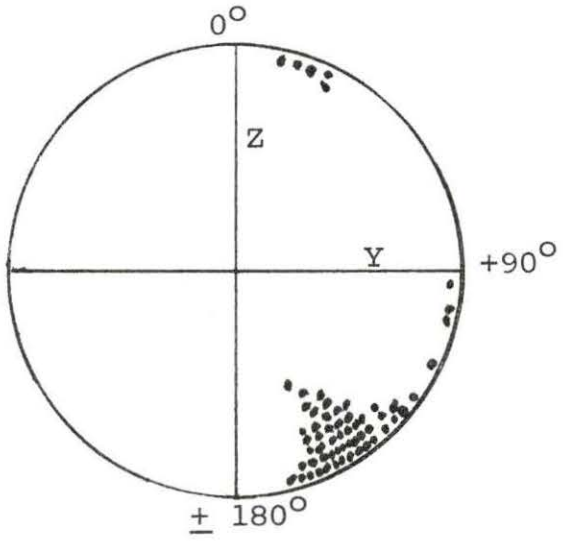


Figure 7. Left sagittal plane

Figures 8 and 9. Scattergrams of half-area QRS vectors in the transverse and left sagittal planes from fifty-nine separate recordings.

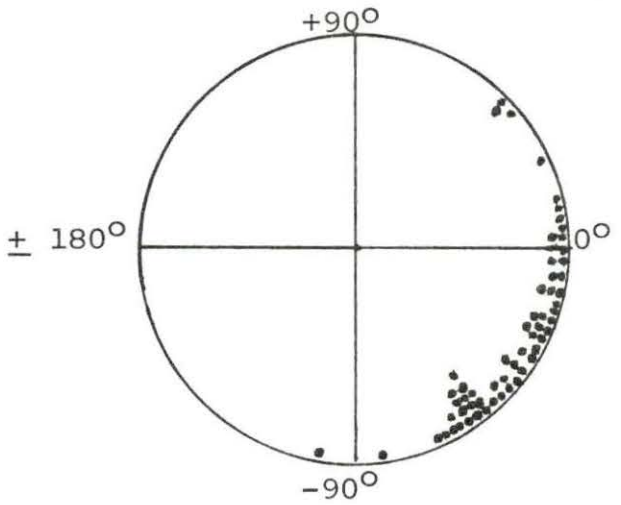


Figure 8. Transverse plane

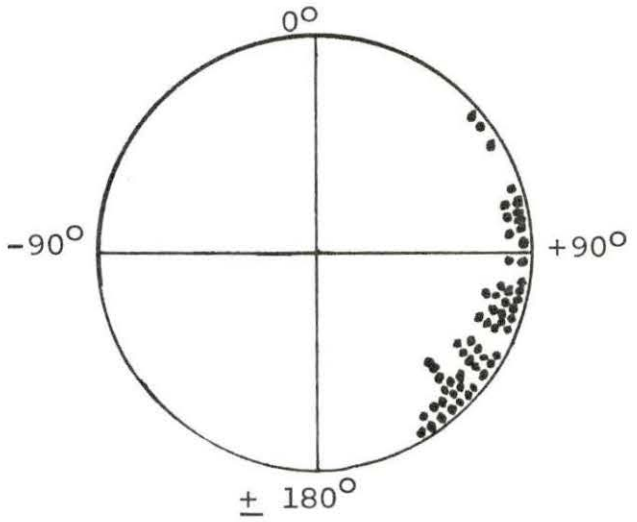


Figure 9. Left sagittal plane

Table 1. Description of canine subjects and causes for rejection.

| Dog No. | Body wt. (kg) | Age | Breed | Sex | Thoracic Ratio |
|---|---|---|---|---|---|
| 1 | 30.4 | 5 yr. | Siberian Husky | M | 1.19 |
| 2 | 16.8 | 1 yr. | Mongrel | F | 1.26 |
| 3 | Ectopic Ventricular beats | | | | |
| 4 | 8.6 | 1 yr. | Mongrel | M | 1.08 |
| 5 | 10.4 | 1 yr. | Beagle | M | 1.33 |
| 6 | 11.4 | 1 yr. | Mongrel | F | 1.15 |
| 7 | 6.8 | 1 yr. | Mongrel | F | 1.26 |
| 8 | 9.1 | 1 yr. | Mongrel | M | 1.09 |
| 9 | 9.5 | 2 yr. | Mongrel | F | .99 |
| 10 | 15.4 | 1 yr. | Mongrel | F | 1.23 |
| 11 | Depressed S-T segment | | | | |
| 12 | 10.4 | 1 yr. | Mongrel | M | 1.12 |
| 13 | 14.1 | 2 yr. | Mongrel | F | 1.10 |
| 14 | 15.4 | 3 yr. | Mongrel | F | 1.15 |
| 15 | 16.8 | 3 yr. | Mongrel | M | 1.28 |
| 16 | Pulmonary consolidation | | | | |
| 17 | Lead II R amplitude more than 3.0 mv. | | | | |
| 18 | Lead II R amplitude more than 3.0 mv. | | | | |
| 19 | 21.8 | 3 yr. | Mongrel | M | 1.12 |
| 20 | 16.4 | 4 yr. | Mongrel | M | 1.15 |
| 21 | 25.4 | 2 yr. | Collie | M | .92 |
| 22 | Mean electrical axis less than $40^{o}$ | | | | |
| 23 | 8.6 | 4 yr. | Dachshund | F | 1.06 |
| 24 | 8.6 | 2 yr. | Beagle | F | 1.08 |

Table 1. Continued

| Dog No. | Body wt. (kg) | Age | Breed | Sex | Thoracic Ratio |
|---|---|---|---|---|---|
| 25 | 7.7 | 1 yr. | Beagle | F | 1.42 |
| 26 | 13.6 | 8 m. | Collie | F | 1.00 |
| 27 | 9.5 | 2 yr. | Cocker Spaniel | F | .93 |
| 28 | 17.7 | 4 yr. | Siberian Husky | F | 1.10 |
| 29 | 32.2 | 11 m. | German Shorthair | M | 1.10 |
| 30 | Lead II R amplitude more than 3.0 mv. | | | | ---------- |
| 31 | 22.8 | 3 yr. | English Pointer | M | 1.20 |
| 32 | 7.7 | 2 yr. | Schnauzer | F | 1.13 |
| 33 | 25.9 | 5 yr. | Weimaraner | F | 1.03 |
| 34 | 6.4 | 2 yr. | Mongrel | F | 1.10 |
| 35 | Lead II R amplitude more than 3.0 mv. | | | | ---------- |
| 36 | Lead II R amplitude more than 3.0 mv. | | | | ---------- |
| 37 | Lead II R amplitude more than 3.0 mv. | | | | ---------- |
| 38 | Lead II R amplitude more than 3.0 mv. | | | | ---------- |
| 39 | 9.5 | 3 yr. | Mongrel | F | 1.13 |
| 40 | 22.3 | 5 yr. | Laborador | M | 1.27 |

Table 2. Magnitude and orientation of maximum QRS vector for frontal, left sagittal, and transverse planes over three consecutive days in each of fifteen dogs.

| | | Frontal Plane | | Transverse Plane | | Left Sagittal Plane | |
|---|---|---|---|---|---|---|---|
| Dog No. | Day | Magnitude (mv.) | Orientation (degrees) | Magnitude (mv.) | Orientation (degrees) | Magnitude (mv.) | Orientation (degrees) |
| 1 | 1 | 2.60 | +71 | 1.30 | -42 | 2.50 | +103 |
| | 2 | 2.85 | +71 | 1.20 | -99 | 2.80 | + 94 |
| | 3 | 2.95 | +62 | 1.80 | -23 | 2.80 | +101 |
| 2 | 1 | 5.15 | +28 | 4.60 | - 3 | 2.30 | +151 |
| | 2 | 3.45 | +41 | 2.60 | 0 | 2.35 | +153 |
| | 3 | 3.50 | +37 | 2.95 | -15 | 2.45 | +127 |
| 4 | 1 | 1.70 | +28 | 1.65 | -65 | 1.80 | +147 |
| | 2 | 2.35 | +26 | 2.15 | +14 | 1.25 | +116 |
| | 3 | 3.05 | +21 | 3.00 | -23 | 1.95 | +145 |
| 5 | 1 | 3.45 | + 8 | 3.65 | +21 | 3.55 | +154 |
| | 2 | 3.55 | +18 | 3.85 | +27 | 2.75 | +152 |
| | 3 | 4.10 | + 9 | 4.10 | +11 | 2.55 | +147 |
| 6 | 1 | 1.60 | +51 | 2.10 | -85 | 2.20 | +162 |
| | 2 | 2.15 | +42 | 2.25 | -83 | 2.35 | +161 |

Table 2. Continued

| Dog No. | Day | Frontal Plane Magnitude (mv.) | Frontal Plane Orientation (degrees) | Transverse Plane Magnitude (mv.) | Transverse Plane Orientation (degrees) | Left Sagittal Plane Magnitude (mv.) | Left Sagittal Plane Orientation (degrees) |
|---|---|---|---|---|---|---|---|
| | 3 | 2.40 | +27 | 2.30 | -71 | 2.30 | +166 |
| 7 | 1 | 2.05 | +41 | 2.15 | +95 | 2.30 | + 17 |
| | 2 | 2.05 | +31 | 2.60 | +99 | 2.65 | + 12 |
| | 3 | 2.65 | +33 | 2.65 | +95 | 2.45 | + 26 |
| 8 | 1 | 2.75 | +22 | 2.80 | -73 | 2.85 | +159 |
| | 2 | 2.70 | +31 | 2.75 | -79 | 2.90 | +154 |
| | 3 | 1.80 | +40 | 2.55 | -77 | 2.85 | +149 |
| 9 | 1 | 2.05 | +37 | 2.20 | -74 | 2.35 | +158 |
| | 2 | 2.20 | +46 | 2.75 | -82 | 2.90 | +158 |
| | 3 | 3.55 | +30 | 3.15 | -19 | 2.75 | +155 |
| 10 | 1 | 2.00 | +33 | 2.20 | -86 | 2.65 | +146 |
| | 2 | 1.95 | +42 | 2.35 | -86 | 2.60 | +150 |
| | 3 | 2.00 | +27 | 1.90 | -67 | 2.35 | +141 |
| 12 | 1 | 2.70 | +40 | 3.65 | -78 | 3.85 | +154 |
| | 2 | 2.05 | +24 | 2.75 | -70 | 2.70 | +158 |
| | 3 | 2.20 | +35 | 2.35 | -81 | 2.50 | +157 |

Table 2. Continued

| Dog No. | Day | Frontal Plane Magnitude (mv.) | Frontal Plane Orientation (degrees) | Transverse Plane Magnitude (mv.) | Transverse Plane Orientation (degrees) | Left Sagittal Plane Magnitude (mv.) | Left Sagittal Plane Orientation (degrees) |
|---|---|---|---|---|---|---|---|
| 13 | 1 | 2.75 | +24 | 2.15 | -97 | 3.45 | +154 |
| | 2 | 3.65 | +21 | 3.45 | - 2 | 2.80 | +153 |
| | 3 | 3.30 | +13 | 3.60 | -31 | 3.75 | +155 |
| 14 | 1 | 3.15 | +28 | 3.00 | -21 | 2.70 | +139 |
| | 2 | 3.25 | +35 | 2.70 | - 9 | 3.00 | +132 |
| | 3 | 2.55 | +45 | 3.30 | -81 | 3.85 | +146 |
| 15 | 1 | 4.45 | +29 | 4.15 | -52 | 4.30 | +146 |
| | 2 | 3.40 | +43 | 3.25 | -74 | 3.90 | +143 |
| | 3 | 3.30 | +37 | 3.60 | -62 | 3.85 | +145 |
| 19 | 1 | 3.00 | +51 | 3.25 | -68 | 3.65 | +146 |
| | 2 | 2.80 | +52 | 4.00 | -65 | 4.15 | +150 |
| | 3 | 2.25 | +45 | 2.60 | -64 | 2.60 | +155 |
| 20 | 1 | 3.85 | +48 | 3.75 | -66 | 4.05 | +147 |
| | 2 | 2.80 | +57 | 2.10 | -49 | 2.06 | +131 |
| | 3 | 4.10 | +38 | 3.50 | -28 | 3.00 | +133 |

Table 3. Magnitude and orientation of maximum QRS vector for frontal, left sagittal, and transverse planes of fourteen dogs.

| | Frontal Plane | | Transverse Plane | | Left Sagittal Plane | |
|---|---|---|---|---|---|---|
| Dog No. | Magnitude (mv.) | Orientation (degrees) | Magnitude (mv.) | Orientation (degrees) | Magnitude (mv.) | Orientation (degrees) |
| 21 | 3.30 | + 41 | 4.00 | - 52 | 3.85 | +147 |
| 23 | 2.75 | + 40 | 4.35 | - 67 | 4.55 | +155 |
| 24 | 3.35 | + 49 | 3.35 | - 55 | 3.60 | +139 |
| 25 | 2.80 | + 40 | 3.10 | - 50 | 2.95 | +144 |
| 26 | 1.45 | +100 | 2.40 | -108 | 2.55 | +152 |
| 27 | 2.25 | + 54 | 2.85 | -107 | 2.85 | +162 |
| 28 | 2.30 | + 52 | 2.40 | - 93 | 2.90 | +142 |
| 29 | 2.90 | + 53 | 2.95 | - 70 | 3.05 | + 26 |
| 31 | 3.25 | + 42 | 4.85 | - 62 | 4.55 | +158 |
| 32 | 3.15 | + 46 | 2.90 | - 65 | 2.95 | +147 |
| 33 | 3.25 | + 80 | 3.90 | - 78 | 4.75 | +139 |
| 34 | 3.30 | + 21 | 3.10 | + 11 | 2.15 | + 21 |
| 39 | 3.00 | + 26 | 2.85 | - 19 | 2.25 | +159 |
| 40 | 2.15 | + 46 | 2.50 | - 75 | 3.10 | +142 |

Table 4. Magnitude and orientation of half-area QRS vector for left sagittal and transverse planes over three consecutive days on each of fifteen dogs.

| Dog No. | Day | Transverse Plane | | Left Sagittal Plane | |
|---|---|---|---|---|---|
| | | Magnitude | Orientation | Magnitude | Orientation |
| 1 | 1 | 1.20 | -52 | 2.20 | +120 |
| | 2 | 1.15 | -60 | 2.00 | +126 |
| | 3 | 1.55 | -60 | 2.10 | +137 |
| 2 | 1 | 4.60 | - 3 | 2.35 | + 98 |
| | 2 | 2.60 | + 5 | 2.25 | +100 |
| | 3 | 2.75 | -23 | 2.35 | +116 |
| 4 | 1 | 1.55 | -12 | 1.50 | +138 |
| | 2 | 2.15 | +14 | 1.10 | + 85 |
| | 3 | 2.85 | -14 | 1.65 | +137 |
| 5 | 1 | 3.00 | + 4 | 2.40 | +128 |
| | 2 | 3.05 | +11 | 1.70 | + 91 |
| | 3 | 3.35 | + 4 | 2.00 | +112 |
| 6 | 1 | 1.45 | -51 | 1.40 | + 91 |
| | 2 | 1.70 | -32 | 1.60 | +110 |
| | 3 | 2.20 | -22 | 1.20 | + 79 |
| 7 | 1 | 1.85 | +48 | 1.40 | + 59 |
| | 2 | 1.80 | +43 | 1.25 | + 49 |
| | 3 | 2.05 | +45 | 1.45 | + 77 |
| 8 | 1 | 2.55 | - 9 | 1.00 | + 83 |
| | 2 | 2.55 | +27 | 1.65 | + 54 |
| | 3 | 2.00 | -47 | 1.00 | +128 |

Table 4. Continued

| Dog No. | Day | Transverse Plane | | Left Sagittal Plane | |
|---|---|---|---|---|---|
| | | Magnitude | Orientation | Magnitude | Orientation |
| 9 | 1 | 1.85 | -29 | 1.40 | + 76 |
| | 2 | 1.55 | -12 | 1.70 | +105 |
| | 3 | 3.10 | -23 | 2.15 | +124 |
| 10 | 1 | 1.70 | - 9 | 1.20 | +110 |
| | 2 | 1.80 | -46 | 1.35 | +108 |
| | 3 | 1.90 | -18 | 1.10 | +113 |
| 12 | 1 | 3.20 | -55 | 2.60 | +136 |
| | 2 | 2.45 | -42 | 1.00 | +131 |
| | 3 | 2.00 | -42 | 1.55 | +124 |
| 13 | 1 | 2.75 | -37 | 1.25 | +124 |
| | 2 | 3.45 | 0 | 1.35 | +101 |
| | 3 | 3.55 | -38 | .70 | +112 |
| 14 | 1 | 3.00 | -26 | 2.60 | +136 |
| | 2 | 2.70 | - 2 | 2.75 | +123 |
| | 3 | 3.30 | -55 | 3.05 | +140 |
| 15 | 1 | 4.10 | -24 | 2.70 | +123 |
| | 2 | 2.65 | -25 | 2.65 | + 78 |
| | 3 | 3.25 | -37 | 2.50 | +132 |
| 19 | 1 | 3.10 | -57 | 3.65 | +143 |
| | 2 | 3.85 | -67 | 4.10 | +147 |
| | 3 | 2.55 | -55 | 2.50 | +144 |
| 20 | 1 | 3.65 | -56 | 3.75 | +138 |
| | 2 | 2.00 | -39 | 2.40 | +102 |
| | 3 | 3.45 | -23 | 2.70 | +112 |

Table 5. Magnitude and orientation of half-area QRS vector for left sagittal and transverse planes of fourteen dogs.

| | Transverse Plane | | Left Sagittal Plane | |
|---|---|---|---|---|
| Dog No. | Magnitude | Orientation | Magnitude | Orientation |
| 21 | 3.55 | -62 | 3.75 | +152 |
| 23 | 3.95 | -56 | 2.20 | +138 |
| 24 | 3.30 | -52 | 3.05 | +120 |
| 25 | 3.00 | -45 | 2.10 | +121 |
| 26 | 2.10 | -99 | 2.35 | +145 |
| 27 | 2.10 | -64 | 1.90 | +110 |
| 28 | 2.00 | -55 | 2.85 | +138 |
| 29 | 1.90 | -20 | 2.30 | + 83 |
| 31 | 4.60 | -56 | 4.15 | +149 |
| 32 | 2.30 | -12 | 2.35 | +105 |
| 33 | 2.95 | -82 | 4.75 | +138 |
| 34 | 3.10 | + 9 | 1.20 | + 89 |
| 39 | 2.65 | -30 | 1.50 | + 72 |
| 40 | 2.30 | -56 | 1.90 | +126 |

Table 6. Pattern of inscription, figure eight (8), clockwise (CW), and counterclockwise (CCW), of the QRS loop in the frontal, transverse, and left sagittal planes over three consecutive days in fifteen dogs.

| Dog No. | Day | Frontal Plane | Transverse Plane | Left Sagittal Plane |
|---|---|---|---|---|
| 1 | 1 | CW | CCW | CCW |
| | 2 | 8 | CCW | CCW |
| | 3 | 8 | CCW | CCW |
| 2 | 1 | CW | CCW | CCW |
| | 2 | 8 | CCW | CCW |
| | 3 | CW | CCW | CCW |
| 4 | 1 | CCW | CCW | CCW |
| | 2 | CCW | CCW | CCW |
| | 3 | CCW | CCW | CCW |
| 5 | 1 | CCW | CCW | CCW |
| | 2 | CCW | CCW | CCW |
| | 3 | CCW | CCW | CCW |
| 6 | 1 | 8 | CCW | CCW |
| | 2 | CW | CCW | CCW |
| | 3 | CW | CCW | CCW |
| 7 | 1 | 8 | CCW | CCW |
| | 2 | 8 | CCW | CCW |
| | 3 | 8 | CCW | CCW |
| 8 | 1 | CCW | CCW | CCW |
| | 2 | CCW | CCW | CCW |
| | 3 | CCW | CCW | CCW |

Table 6. Continued

| Dog No. | Day | Frontal Plane | Transverse Plane | Left Sagittal Plane |
|---|---|---|---|---|
| 9 | 1 | 8 | CCW | CCW |
| | 2 | CCW | CCW | CCW |
| | 3 | CCW | CCW | CCW |
| 10 | 1 | CCW | CCW | CCW |
| | 2 | CCW | CCW | CCW |
| | 3 | CCW | CCW | CCW |
| 12 | 1 | CCW | CCW | CCW |
| | 2 | CCW | CCW | CCW |
| | 3 | CCW | CCW | CCW |
| 13 | 1 | CCW | CCW | CCW |
| | 2 | 8 | CCW | CCW |
| | 3 | CCW | CCW | CCW |
| 14 | 1 | CCW | CCW | CCW |
| | 2 | CCW | CCW | CCW |
| | 3 | CCW | CCW | CCW |
| 15 | 1 | CCW | CCW | CCW |
| | 2 | CCW | CCW | CCW |
| | 3 | CCW | CCW | CCW |
| 19 | 1 | CCW | CCW | 8 |
| | 2 | 8 | CCW | 8 |
| | 3 | 8 | CCW | 8 |
| 20 | 1 | CCW | CCW | CCW |
| | 2 | CW | CCW | CCW |
| | 3 | 8 | CCW | CCW |

Table 7. Pattern of inscription, figure eight (8), clockwise (CW), and counterclockwise (CCW), of the QRS loop in the frontal, transverse, and left sagittal planes of fourteen dogs.

| Dog No. | Frontal Plane | Transverse Plane | Left Sagittal Plane |
|---|---|---|---|
| 21 | 8 | CCW | CCW |
| 23 | CCW | CCW | CCW |
| 24 | CCW | CCW | CCW |
| 25 | CW | CCW | CCW |
| 26 | CCW | CCW | CCW |
| 27 | 8 | CCW | CCW |
| 28 | CCW | CCW | CCW |
| 29 | CW | CCW | CCW |
| 31 | CW | CCW | CCW |
| 32 | 8 | CCW | CCW |
| 33 | CW | CW | CCW |
| 34 | CCW | CCW | CCW |
| 39 | CW | CCW | CCW |
| 40 | CCW | CCW | CCW |

Table 8. Analysis of variance of the frontal plane maximum vectors' magnitude and orientation in fifteen dogs comparing the variation among dogs and among serial recordings.

| Variable | Source | df | Mean square | F value |
|---|---|---|---|---|
| Maximum | Dogs | 14 | 1.3126 | 4.39** |
| Magnitude | Days | 2 | 0.1184 | <1.00 |
| | Error | 28 | 0.2987 | |
| Maximum | Dogs | 14 | 511.5156 | 10.10** |
| Orientation | Days | 2 | 109.3542 | 2.16 |
| | Error | 28 | 50.6486 | |

**Significant at the 0.01 level

Table 9. Analysis of variance of the transverse plane maximum and half-area vectors' magnitude and orientation in fifteen dogs comparing the variation among dogs and serial recordings.

| Variable | Source | df | Mean square | F value |
|---|---|---|---|---|
| Maximum | Dogs | 14 | 1.2278 | 3.67** |
| Magnitude | Days | 2 | 0.1193 | <1.00 |
| | Error | 28 | 0.3345 | |
| Maximum | Dogs | 14 | 6813.9171 | 5.92** |
| Orientation | Days | 2 | 1521.1618 | 1.32 |
| | Error | 28 | 1150.9447 | |
| Half-area | Dogs | 14 | 1.3495 | 4.01** |
| Magnitude | Days | 2 | 0.4028 | 1.19 |
| | Error | 28 | 0.3364 | |
| Half-area | Dogs | 14 | 2112.2066 | 8.43** |
| Orientation | Days | 2 | 617.0890 | 2.46 |
| | Error | 28 | 250.5461 | |

**Significant at the 0.01 level

Table 10. Analysis of variance of the left sagittal plane maximum and half-area vectors' magnitude and orientation in fifteen dogs comparing the variation among dogs and serial recordings.

| Variable | Source | df | Mean square | F value |
|---|---|---|---|---|
| Maximum | Dogs | 14 | 0.9459 | 4.14** |
| Magnitude | Days | 2 | 0.2012 | <1.00 |
| | Error | 28 | 0.2282 | |
| Maximum | Dogs | 14 | 3878.63 | 7.34** |
| Orientation | Days | 2 | 72.621 | <1.00 |
| | Error | 28 | 528.0657 | |
| Half-area | Dogs | 14 | 1.5609 | 9.14** |
| Magnitude | Days | 2 | 0.2087 | 1.22 |
| | Error | 28 | 0.1706 | |
| Half-area | Dogs | 14 | 1238.6083 | 4.36** |
| Orientation | Days | 2 | 1352.3103 | 4.75* |
| | Error | 28 | 284.6749 | |

*Significant at the 0.05 level

**Significant at the 0.01 level