Fundamentals of Electrocardiography and Vectorcardiography

By

LAWRENCE E. LAMB, M.D.

Director of Cardiology and
Chief, Department of Internal Medicine
Air University
School of Aviation Medicine, USAF
Randolph Air Force Base, Texas
Consultant in Cardiology
3700th USAF Hospital
Lackland Air Force Base
San Antonio, Texas

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To My Friend and Teacher

Dr. Pierre W. Duchosal

Geneva, Switzerland

Preface

THE PURPOSE of this book is to set forth the basic fundamentals of electrocardiography and vectorcardiography. The rapid growth of this important field behooves a clear understanding of the principles involved. It is no longer sufficient to memorize patterns, or for that matter to memorize a group of rules incorporated under the term vector electrocardiography. The reader should learn from the beginning the laws governing the measurement of potential from the surface of a volume conductor, the effects of eccentricity of the heart, the effects of lead length on measurements, and the very definite limitations of many of the instruments currently employed (direct writing instrument in particular). He should learn the fundamentals of vector analysis as a mathematical science, e.g., unless one understands the fundamental difference between polygons and coordinate graphs there is not much probability of comprehending the difference between vectorcardiograms and electrocardiograms, or their similarities.

The manuscript begins at the very beginning with the simplest of vector concepts. More detailed or technical points are placed as footnotes for the more exacting reader and to avoid confusing the beginner. An abundant group of illustrations are used to clarify the text and to help the reader develop a three dimensional concept. Spatial models of vectorcardiograms are used as a further aid in grasping the spatial orientation of the electrical forces.

The emphasis on the mean spatial QRS-T angle in recent years has made it desirable for the practitioner to be able to determine this angle from the routing 12 lead electrocardiogram. For this purpose a simple chart is provided that may be used like an ordinary road mileage chart without resorting to cumbersome calculations.

The text includes the most modern concepts of cellular activity as well as reference to important basic experiments and concepts too soon forgotten. It is intended as a simplified book for the beginner as well as detailed footnotes and new concepts for the authority. The material points up the value of European concepts of electrical moment, not commonly employed by American cardiologists. A large number of authentic clinical illustrations are included to provide practical application.

L.E.L.

Acknowledgments

I WISH TO TAKE this opportunity to thank the following people who have helped to make this book possible. In particular I wish to thank Colonel Archie A. Hoffman for constructive suggestions, Dr. Julian Ward for calculating the Vectorcardiogram Standardization Charts included in the appendix, and Dr. M. B. Danford and Mr. Richard McNee of the Department of Biometrics for performing the calculations for the Spatial Angle Chart. I am especially pleased with the drawing of the illustrations done by Mr. Leonard F. Carol and assistants. The work done by technicians, Sara Johnson, Harvey Hamel, William Yarwood and Robert Wanner, in preparing the electrocardiograms and the vectorcardiogram models was an important contribution. I am indebted to Hedwig Richter and Patricia Dyer for the tedious job of typing the manuscript. The photography was done by Captain Arthur Thiesen, Sergeant Harvey Kohnitz and staff. To all of these people and the numerous other members of the staff of the School of Aviation Medicine that have helped, I wish to say thank you.

L.E.L.

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Fundamentals of Electrocardiography and Vectorcardiography

I

Fundamental Vector Concepts

ELECTROCARDIOGRAPHY strives to measure potential (forces) created by the heart in terms of magnitude, direction and duration of action. Vector concepts greatly simplify analysis of these forces. The use of vectors to express mathematical quantities is as old as mathematics itself. They were applied to electrocardiography by Einthoven. The understanding of electrocardiography begins with an understanding of simple vector principles.

What Is a Vector? It is a symbol used to describe the characteristics of a force. The magnitude of the force is represented by the length of the vector. The arrow head (terminus) of the vector indicates the direction of the force. A vector used to describe a force in two dimensions (flat surface) is drawn as a flat arrow. A spatial vector representation is used to describe a three dimensional force (Fig. 1). The duration of action of a force is not expressed by a

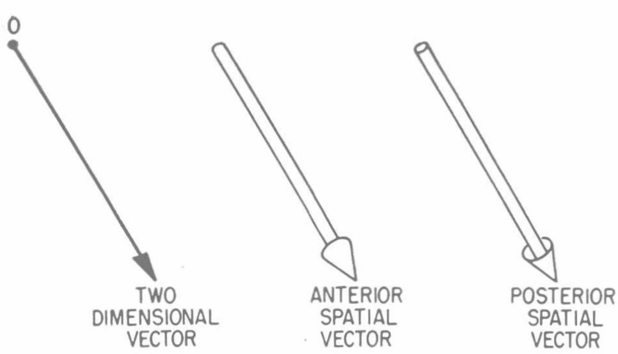

Figure 1.

vector unless the magnitude has been converted to time units. A force of one dyne acting for ten sec. is still a one dyne force represented by one unit length (1 unit equals 1 dyne). Expressed in time units as dynes × seconds, such a force would be equal to ten dyne seconds and represented by ten units length (1 unit equals 1 dyne second).

What Is the Point of Origin? The maximum effect of a force occurs at a point. The force is said to act on this point. In vector terminology this point is called the point of origin. One end of any vector is its point of origin and the other end is the head (terminus) indicating the direction of the vector and extent of its magnitude.

What Is an Instantaneous Vector? A vector without duration of time is an instantaneous vector. It acts only at a point in time. In electrocardiography it is often of interest to speak of a vector acting at one particular time interval, thus the vector acting momentarily at .04 sec. after the onset of an event is spoken of as the .04 sec. vector. Such a vector is an instantaneous vector and acts only at that time interval. At .05 sec. after the onset of the same event the vector might be entirely different in magnitude and direction. The .05 vector would be another instantaneous vector.

What Is a Resultant Vector? When two or more vectors are acting on a common point of origin, their net effect can be represented by a single vector. Such a vector is called a resultant vector (Fig. 2). It represents the effective force of all the vectors. *The resultant vector is not equal to the magnitude of all the vectors acting on the point, nor does it have a consistent relationship to their magnitude.*

What Is a Coordinate? Any straight line drawn through the point of origin is a coordi-

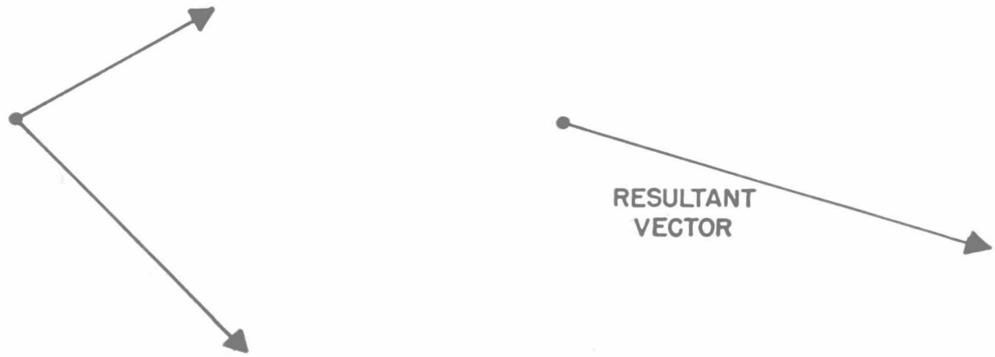

Figure 2.

nate. Its length can be marked off into units of measure. The effect of a vector in the direction defined by the coordinate (line) can be determined by constructing a perpendicular from the coordinate to the tip of the vector (Fig. 3). The units along the coordinate equals the effect of

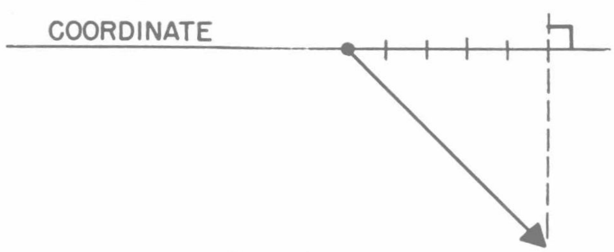

Figure 3.

the vector in that direction. This value is the coordinate value of the vector. The value may be expressed as positive or minus units by designating one end of the coordinate positive and the other negative.

The coordinate value of the vector is spoken of as its projection upon the coordinate. All electrocardiographic leads are coordinates and measure forces that are projected upon them. Any vector can be described in terms of its projection upon three mutually perpendicular coordinates (X, Y, Z). The X coordinate (transverse) defines the left to right location of the terminus. The Y coordinate (vertical) defines the vector terminus above or below the point of origin. The Z coordinate (sagittal) locates the vector terminus anterior or posterior to the point of origin (Fig. 4).

What Are Component Vectors? The units of magnitude measured upon the coordinates X, Y,

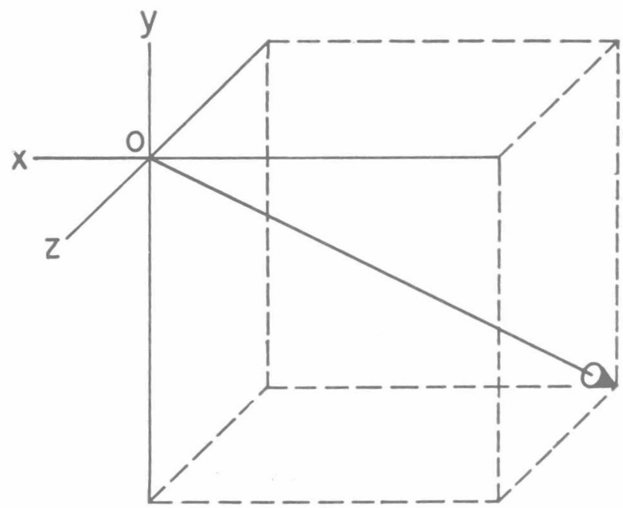

Figure 4.

Z can be expressed as vectors. The three vectors, X, Y, Z, are component vectors. The resultant of three such vector components is equal to the magnitude and direction of the spatial vector. They are perpendicular vector components (Fig. 5). Any spatial vector can be resolved into its three perpendicular components. The magnitude of the spatial vector can be calculated from its perpendicular components from the simple formula:

$$(\text{Spatial vector})^2 = X^2 + Y^2 + Z^2.$$

Any spatial vector may have multiple component vectors and multiple coordinates but it can have only three mutually perpendicular coordinates and three mutually perpendicular components.

How Is the Coordinate Value of a Vector Calculated? When the angle between a vector and a given coordinate is known the projection

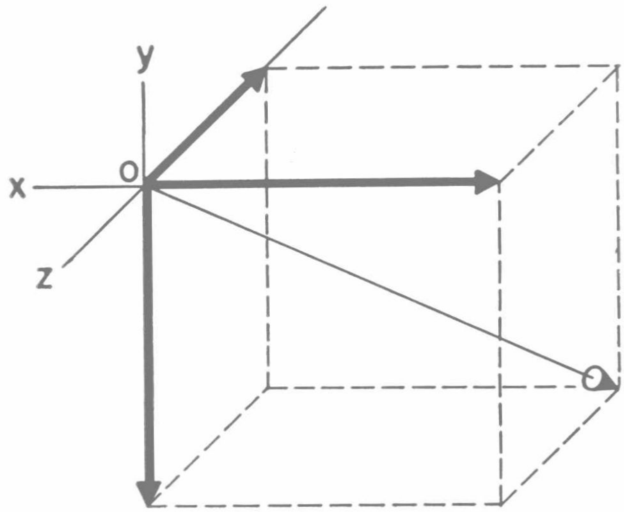

Figure 5.

of the vector on the coordinate can be calculated without constructing a perpendicular (Fig. 6). This is done by using the principle of the right triangle. The vector is the hypotenuse of a right triangle and the coordinate is the adjacent side. The cosine* of the angle times the magnitude of the vector equals its coordinate value:

$$\text{Cos} \propto \times \text{Vector Magnitude} = \text{Coordinate Value.}$$

What Is a Plane? A plane expresses two dimensions of a vector and has two perpendicular coordinates. It is a flat surface. *The frontal plane* (X, Y) is made up of the X, Y coordinates. *The transverse plane* (X, Z) is composed of the X, Z coordinates. *The sagittal plane* (Z, Y) is the Z, Y coordinates. These planes are mutually perpendicular to each other. Any two of them can be used to determine a spatial vector as two perpendicular planes include all three mutually perpendicular coordinates (X, Y, Z).

The principle of measuring a vector from its projection upon a plane or flat surface is frequently used in electrocardiography. The magnitude of a vector measured by a plane diminishes as the vector is rotated away from its flat surface (Fig. 7). Considering the frontal plane, as the vector is rotated away from the X, Y coordinates the frontal plane vector becomes smaller. Finally, when the vector is parallel to the Z coordinate its entire magnitude is measured by the Z coordinate. Such a vector has no projection upon the X or Y coordinate and has no magnitude value in the frontal plane. Both X and Y are perpendicular to Z and the frontal plane is perpendicular to such a vector. A simple rule is illustrated, *there is no force at any point on a plane perpendicular to a vector.* The direction of a vector can be determined by locating its perpendicular plane as the vector is 90° away from this plane.

*The cosine of an angle is equal to adjacent side divided by the hypotenuse.

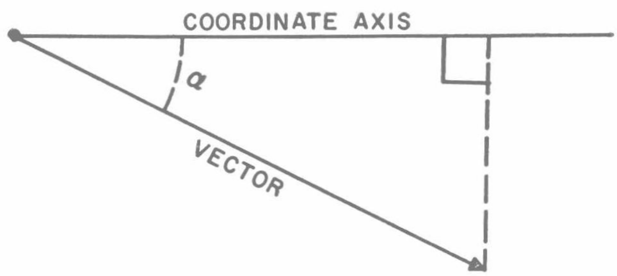

Figure 6.

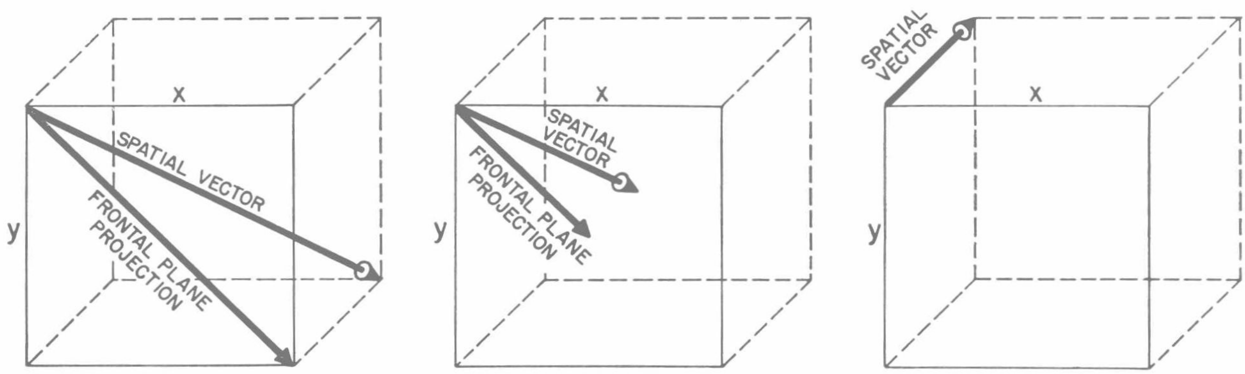

Figure 7.

What Is the Law of Parallelograms? The resultant of two vectors acting upon a common point can be determined by constructing a parallelogram (Fig. 8). The two vectors are two adjacent sides (a, b) of the parallelogram. The diagonal of the parallelogram is the resultant vector (c). The magnitude of the vectors acting on the common point can be determined from the sides of the parallelogram (a, b'). Note that $b = b'$ as they are opposite sides of the parallelogram. Knowing only a and c the magnitude of the vector b can be determined by merely measuring the distance between vector a and c or the length of b'. The two adjacent sides of the parallelogram equals the magnitude of the acting vectors and the diagonal equals their effect or resultant.

It is very important to realize that the diagonal of the parallelogram is not equivalent to the magnitude of the acting vectors. Any triangle is a semiparallelogram. When one side of a triangle is a component (acting) vector (a) and the other the resultant vector (c) the other component vector (b) can be determined from the law of parallelograms.

Figure 8.

The Law of Simple Consecutive Vector Addition. The addition of vectors upon a common point, one after another, will cause the resultant vector to change with the addition of each vector. Consider eight vectors of equal magnitude (P) consecutively added to each other upon a common point (O) and directed 45° away from each other (Fig. 9). The addition of vector 2 to vector 1 creates the resultant 1. Note that R_1 is the diagonal of a semiparallelogram while V1 and V2 are the adjacent sides of the parallelogram. The addition of vector 3 to vectors 1 and 2 creates the resultant vector 2.

The addition of each new vector causes the resultant vector to rotate a distance equal to the added vector's magnitude. The rotating resultant vector describes an external pathway, comprised of the sides of a polygon. The length of the sides of the polygon is equal to the total magnitude of all the vectors acting on the common point. In this instance the magnitude of the eight vectors acting on the common point is 8P. The sum of the length of the sides of the polygon is also 8P. The graph of the rotating resultant vectors is a polygon. The resultants

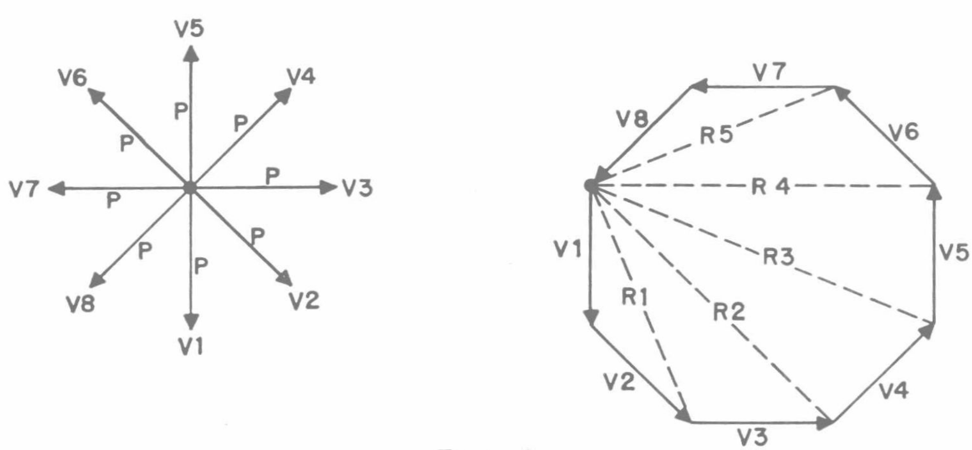

Figure 9.

originating from the center of origin may be called central resultants. Note that the magnitude of the acting vectors is never equal to the central resultants. A law may be formulated: *The consecutive addition of vectors upon a common point will cause the central resultant to rotate, describing a polygon. The length of the sides of the polygon is equal to the magnitude of the vectors added to each other.**

The Law of Simple Consecutive Vector Subtraction. The subtraction of vector forces, one after another, from a common point creates a similar situation as consecutive addition. Given eight vectors of equal magnitude (P) directed 45° away from each other, there will be no effective force until subtraction begins. With the subtraction of vector 1 an effective force is created by the remaining seven vectors. The subtraction of vector 2 changes the resultant again. The resultant vector changes with each additional subtraction. A law may be formulated: *The successive subtraction of vectors from a common point causes a resultant vector to be rotated describing a polygon. The length of the sides of the polygon is equal to the magnitude of the vectors subtracted.* In either addition or subtraction the shape of the polygon will also depend upon the order of addition or subtraction (Fig. 10).

The Law of Multiple Simultaneous Vector Addition. The addition of vectors upon a common point may be complicated by the simultaneous addition of more than one vector. Consider two vectors *a* and *b* added simultaneously to a previously existing vector, A (Fig. 11). Vectors *a* and *b* have a resultant effect, *c*, the diagonal of a parallelogram. The action of these two vectors is equal to vector *c*. When vectors

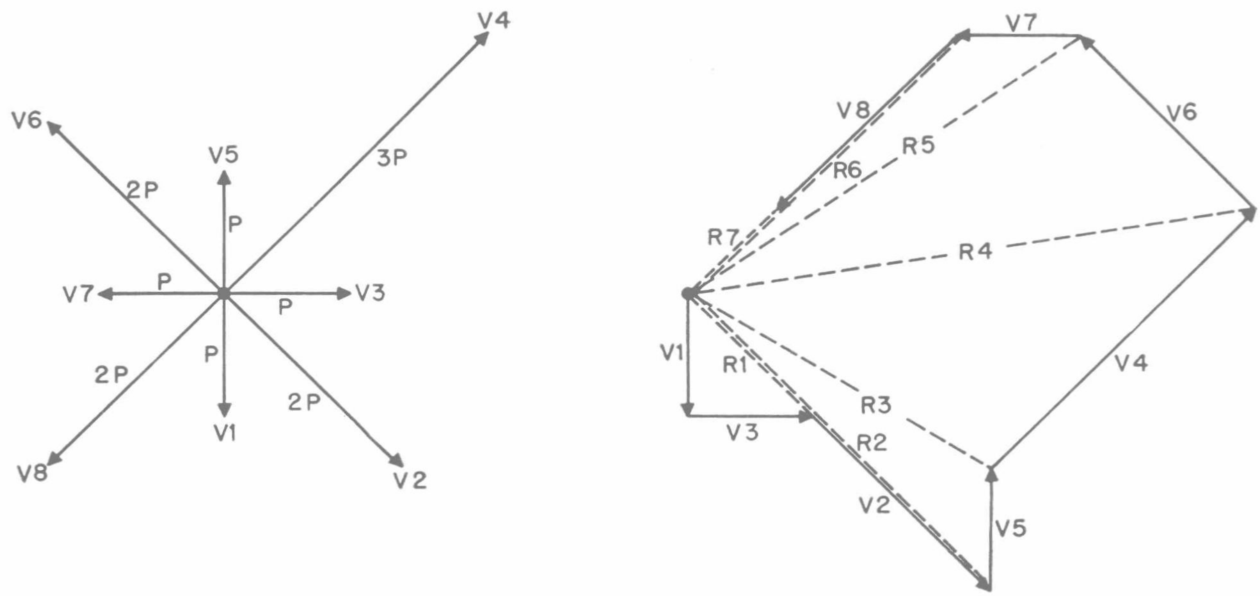

Figure 10. The irregular shaped polygon is created by unequal vectors acting upon the point of origin. Note that the simultaneous action of such unequal vectors would have a resultant, in this case R7. The resultant of several vectors acting on a common point can always be determined in this manner. In the previous illustrations the resultant has been zero and the polygon was a closed polygon.

*Figure 9 is drawn to scale as geometric proof of the law. The method of polygon formation must apply to every situation wherein vectors are assumed to act upon a common point or center. The polygon finds its origin in the law of parallelograms. Whenever instantaneous resultant vectors are assumed to act on a point the sides of a polygon can be constructed. The sides of the polygon then represent the magnitude of the component vectors. The reader is referred to: White, Harvey E.: *Classical and Modern Physics.* New York, Van Nostrand Company, Inc., 1940, pp. 25-26, and Kimball, A. L.: *A College Text-Book of Physics,* Fifth Edition, New York, Henry Holt and Company, 1939, p. 11.

a and *b* are added to vector *A* it is exactly the same as if vector *c* had been added to vector *A*. Knowing vector *A* and the new resultant (*B*) created by the addition of vector *c*, one can determine vector *c* by measuring the distance between *A* and *B*. A law may be formulated: *The simultaneous addition of two or more vectors to a previously existing vector will cause it to rotate describing one side of a polygon. The length of the side is equal to the magnitude of the resultant of the simultaneously added vectors.* A similar relationship exists for subtraction.

What Is a Coordinate Graph? Electrocardiographic leads are coordinate graphs in contradistinction to vectorcardiograms which are polygons. They are vectors graphed upon a coordinate in a linear fashion. Extend coordinates X and Y through the circular type graph of consecutive vector addition (Fig. 12). Each central resultant can be projected upon the coordinates in a linear fashion. This creates a coordinate graph of the x components of central resultants and another graph of the y components of the central resultants. Note that such graphs are graphs of the central resultants and not the sides of the polygon. As shown above the magnitude of vectors acting on a common point is measured by the sides of a polygon. By indirect calculation or geometric construction the polygon can be obtained from linear coordinate graphs, but such a procedure must be carried out before one can speak correctly in terms of vector magnitude.*

What Is an Absolute Linear Graph? The central resultants may be graphed upon a time base to form a linear graph (Fig. 13). A popular application to vectorcardiography is to so graph the instantaneous resultant spatial vectors. It is clear from a fundamental vector approach that such central resultants in no way represent the magnitude of the component vectors acting upon a common point and unless one knows the angles between such central resultants the sides of the polygon cannot be reconstructed. These measurements have been called the absolute vectorcardiogram. A linear graph of the central resultants is called an absolute graph. Actually the use of the term absolute is a misnomer in

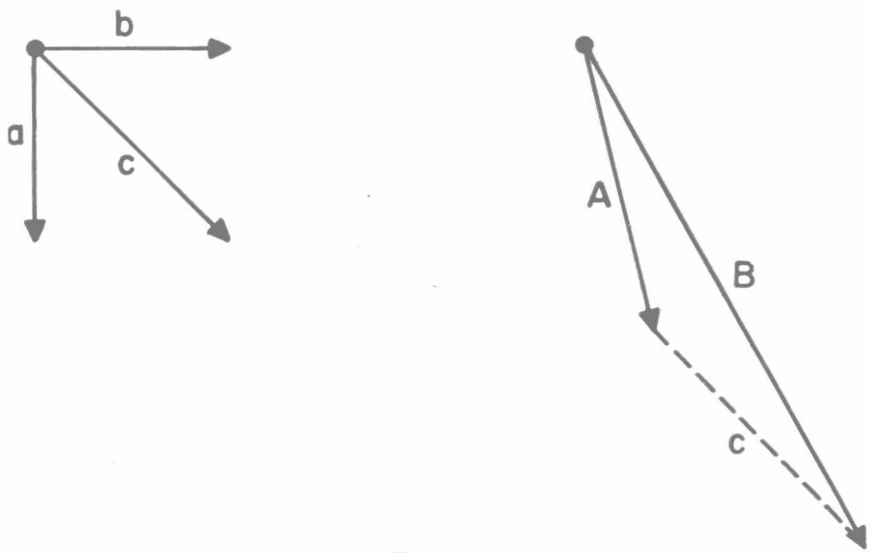

Figure 11.

*Each side of the polygon can be determined by obtaining its x and y component. The x component is the difference in amplitude of the central resultant projection upon x coordinate for that time interval and the y component is the difference in amplitude of the central resultant projected upon the y coordinate. The side for this time interval or for the added vector is then obtained from the formula $x^2 + y^2 = \text{Side}^2$ or by simple graphic construction.