Planar Dipole Loops

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This is a theoretical discussion of characteristics of body surface potentials produced when the equivalent heart dipole is confined to a plane. Various experimental findings are unified by a single theory, and broad comprehension of the potential behavior is possible.

Vectorcardiographic loops are often found to lie essentially in a plane, the ratio of maximum length to maximum width-viewed-edgewise usually being at least 10:1 in normals. This interesting characteristic may even be more pronounced and frequent when corrections for known errors of presently used systems of vectorcardiography are introduced. Although no particular physiological significance or explanation for planar loops has been advanced, it is nevertheless useful to investigate special characteristics of body-surface potentials encountered when the dipole vector is confined to a plane. Such an investigation unifies several seemingly unrelated phenomena previously found by experiment, such as nulls in the transitional zone and "decrement" patterns. A comprehensive view of these and other characteristics is helpful in understanding such behavior, and serves as a guide for future experimental observations. Characteristics described in this paper are readily observed experimentally in human subjects whose dipole vectors are reasonably confined to a plane. They are all explainable theoretically and are representable geometrically in image space in accordance with principles previously presented.

Discussion

Body Surface Potentials. Assumptions underlying this analysis are (1) the human body is a resistive, linear medium (either homogeneous or heterogeneous) having the same shape as the human torso, (2) electric activity in the heart may be represented at each instant by a single equivalent current dipole, and (3) the equivalent dipole is fixed in location during any given complex. These assumptions have been discussed in detail and experimental evidence concerning their applicability has been presented. With these assumptions, the potential produced at any body-surface point with respect to the dipole mid-potential (arbitrarily taken as zero) may be expressed as

\[ V = \mathbf{c} \cdot \mathbf{p} = c_u p_u + c_v p_v + c_w p_w \]

where \( \mathbf{p} = up_u + vp_v + wp_w \) is the heart dipole vector* with scalar components \( p_u, p_v \) and \( p_w \) which depend upon electric activity in the heart, and \( \mathbf{c} = uc_u + vc_v + wc_w \) is the image vector with scalar components \( c_u, c_v \) and \( c_w \) which depend upon the size, shape and characteristics of the medium, the dipole location and the boundary point where the potential is \( V \). Orthogonal coordinates are symbolized by \( u, v \) and \( w \) with associated unit vectors \( \mathbf{u}, \mathbf{v} \) and \( \mathbf{w} \), respectively, and are arbitrarily oriented with respect to anatomic body axes to achieve generality.

If the dipole loop, the locus of the tip of \( \mathbf{p} \) as a function of time, is confined to a plane, this means that the variations of \( \mathbf{p} \) are two-dimensional. Without loss in generality, the coordinate system may be oriented so that \( \mathbf{p} \) lies in the \( w \)-plane, in which case \( p_w = 0 \). Hence, the planar dipole loop is defined by

\[ \mathbf{p} = up_u + vp_v \]

* All vectors are set in bold face type throughout this paper.
Bipolar Nulls. The bipolar null is a bipolar lead taken directly from the subject which displays zero potential difference during a given complex. Such nulls are occasionally found fortuitously in some patients using standard electrocardiographic leads. When electrode A in figure 1 is placed at any arbitrary fixed point on the body surface, and search electrode B is used as an exploring electrode, it will be found that a very small potential difference can be achieved between electrodes by suitable body search, depending upon the degree to which the subject's equivalent dipole is confined to a plane. For an exactly planar loop the potential difference will be zero.

Theoretic explanation of this phenomenon can be seen by examining \( V_A = A \cdot \mathbf{p} \) and \( V_B = B \cdot \mathbf{p} \). Potential difference \( V_A - V_B = (A - B) \cdot \mathbf{p} \) is zero when image vector \( A - B \) is perpendicular to the plane to which \( \mathbf{p} \) is confined, a physically realizable condition. Geometric representation of the null condition is shown in figure 2 where the dipole vector is confined to the \( uv \)-plane and image vector \( A - B \) is parallel to the \( w \)-axis. Because the projection of \( \mathbf{p} \) onto image vector \( A - B \) is zero during the entire complex, the potential difference \( V_A - V_B \) will likewise be zero.

No matter what arbitrary point \( A \) is taken initially, a search location \( B \) may be found such that image vector \( A - B \), associated with electrodes A and B, is perpendicular to the plane of the loop, because the image surface\(^9\) has a regular contour. Thus, an infinite number of such bipolar nulls may be found, one for each initial choice of \( A \), but there is one and only one body-surface point \( B \) that will produce a null for a given location of \( A \).

In practice the degree to which the dipole loop is confined to a plane must be recognized in tempering the mathematical exactitude of this principle.

Constant Waveform Loci. Another special characteristic of body-surface potentials observable when the dipole loop is planar gives insight into "decrement" patterns\(^3\) and contains the bipolar null as a special case. When electrode A in figure 3 is placed at any arbitrary point on the body surface, a locus on the body may be established experimentally with search electrode D by demanding that the...
FIG. 3 & 4. A constant waveform locus can be found with respect to arbitrary body-surface electrode A using search electrode D, if subject's loop is confined to a plane. Geometric representation of the condition for this locus in image space (right) shows dipole loop in uw-plane and unipolar image vectors A and D (associated with anatomic points A and D, respectively) which terminate on image surface. When image vector A — D lies in a plane parallel to the uw-plane, as shown, the projection of p onto A — D yields an invariant shape proportional to p, only. Null point B, with associated image vector B, is where polarity reversal takes place at which point A — D is perpendicular to the plane of p. The image locus is depicted behind the uw-plane in this instance.

complex under study have the same shape for all search locations, but not necessarily constant amplitude. This has been readily observed on subjects over a limited range of the body surface. Thorough and complete search reveals a polarity reversal along the locus in which the same shape is observed in inverted complexes.

Theoretical exploration of this phenomenon gives a comprehensive understanding of observations and enables generalization. The potential difference $V_A - V_D = (A - D) \cdot p$ displays invariant waveshape when the plane containing image vector $A - D$ is parallel to the w-axis, as shown in figure 4. There is no loss in generality in rotating the coordinate system about the w-axis so that the constant waveform locus is parallel to the uw-plane in image space. For this condition, the potential difference is given by

$$V_A - V_D = [(A_x - D_x)v + (A_w - D_w)w] \cdot [wp_u + wp_w] = (A_x - D_x)p_w$$

and is proportional to $p_w$ only thus proving the constant shape characteristic. Since the magnitude of $A_x - D_x$ (the v-component of $A - D$) varies as the locus is traversed, this accounts for the changing amplitude of the complex. Because $A_x - D_x$ can be either positive or negative, $V_A - V_D$ will undergo a polarity reversal, being of one polarity when the locus lies to one side of the image line joining the tips of $A$ and $B$, and of the opposite polarity when on the other side. The case of $A_x - D_x = 0$ occurs under two conditions: (1) when electrode D is directly at A (obviously) and (2) when D is at location B. The latter case is the bipolar null condition discussed previously, since image vector $A - D = A - B$ is then perpendicular to the plane of the loop.

Study of this phenomenon reveals that for any given arbitrary reference electrode A, a constant waveform locus may always be found for any initial choice of electrode D site, but the waveshape will depend upon the initial choice of D. Thus, there are an infinite number of such loci, all passing through the point A, along which an invariant waveform will be observed but for each locus a different waveform will pertain. Along each locus a continuous change in amplitude will exist, the locus will close on itself in traversing the body, and
null point

null point

\[ \vec{E} - \vec{C} = (E_x - C_x) \hat{x} + (E_y - C_y) \hat{y} \]

FIG. 5. Constant waveform locus with respect to the Wilson central terminal occurs when image vector from point C (representing the three resistor junction in image space) to point E (representing the search electrode in image space) is confined to a plane parallel to the uv-plane. Image locus is shown behind the uv-plane in this instance. Two null points occur on locus when \( E - C \) is perpendicular to plane of loop. Shaded portion of limb lead triangle, R, L, F lies behind plane of image locus.

will display a null at some point other than A at which a polarity reversal takes place.

Cancellation methods\(^7\) may be devised for outlining these loci with precision, but unless the subject's loop is very nearly in a plane such refined procedures are not worth applying since invariance of waveshape depends on the degree to which the dipole loop lies in a plane. One such method entails use of a potentiometer connected between search electrode D and another fixed point of mirror pattern (beyond point B) on the same locus. Cancellation between electrode A and the potentiometer tap occurs as D is moved along the correct locus, provided the potentiometer tap is appropriately adjusted to compensate for inequality of amplitudes.

Transitional Zone. The transitional zone,\(^8\) a readily observable phenomenon, has been defined as that body-surface locus for which the complex under study displays biphasic deflections (net area under complex equal to zero), measured with respect to the Wilson central terminal. It is well known that this biphasic locus displays a polarity reversal. The transitional zone is essentially the same type of phenomenon as the constant waveform locus just described, except a three-resistor junction is used as a reference point rather than some fixed body-surface point.

The image space representation in figure 5 reveals, in geometric terms, the laws governing this type of locus for the case of a planar loop. The Wilson central terminal is located in image space at the median point C of the limb lead triangle\(^8\) and image point E corresponds to the location of a search electrode on the body. The potential difference \( V_s - V_c = (E - C) \cdot p \) displays an invariant waveshape when image vector \( E - C \) lies in a plane parallel to the w-axis as shown in figure 5, which is the same condition previously mentioned for constant waveform loci with respect to a fixed body-surface point. When the coordinate system is rotated about the w-axis so that the image locus is parallel to the uw-plane in image space, a non-restrictive maneuver, the potential difference is given by \( V_s - V_c = (E_x - C_x) \hat{p} \), thus proving the invariant wave shape property. There are an infinite number of such loci, representable in image space by the intersection with the image surface of any plane containing image point C which is also parallel to the w-axis. For the particular locus yielding biphasic waveshape, this becomes the transitional zone. It can be seen in figure 5 that the magnitude of \( E_x - C_x \), the \( v \)-component of \( E - C \), varies as the locus is traversed and this explains the amplitude changes observed along the locus. Because \( E_x - C_x \) can be positive or negative, the polarity reversal observed experimentally is also expected from theory. In addition, there will always be two points along the transitional zone (or any of these constant waveform loci) which display nulls since there are two points where \( E_x - C_x = 0 \), and this too agrees with experimental observations. It should not be inferred that a transitional zone can be found, qualitatively, only in the case of a planar loop. However, two null points on this zone are found only in the case of a planar loop. Loci of this type are also obtainable with other types of resistor junctions.
Body Locus of Loop Plane. It is possible to determine experimentally, in the case of a planar loop, a locus on the body surface which corresponds electrically to the plane of the loop. This locus is found approximately at points of maximum amplitude of all possible constant waveform loci passing through an arbitrary fixed body-surface point A.

One of several possible methods for establishing this locus entails finding multiple bipolar nulls. It is necessary to use a preamplifier in cascade with an ordinary electrocardiograph to achieve adequate sensitivity. For an arbitrary initial point such as A, a bipolar null is obtained as previously described (fig. 1). Then the location of A is shifted anatomically toward that location of B which yielded the bipolar null, and a new location of B is determined for null. Continuing this procedure, electrodes A and B converge toward each other and, in so doing, establish one point on the body surface which lies electrically in the plane of the dipole loop. The entire procedure may be repeated for any number of different initial starting points for electrode A, thus establishing any number of points on the desired locus. Although time consuming, it is possible in this manner to map out on the body surface the entire closed locus which corresponds electrically to the plane of the dipole loop. The anatomic locus generally will not lie in a plane because of the electrical distortion effects of body contour and dipole location, even though this locus lies in the plane of the loop in image space. This locus has no special application at present but its future utility may lie in research determinations of the two unknown dipole components. Chief obstacle is devising a method for securing two orthogonal leads solely from body-surface measurements, which appears insurmountable even with knowledge of the body surface locus which contains the dipole loop.

Planar Loop Tests. While the dipole loop is never confined precisely to a plane in practice, the minimum potential difference obtainable from bipolar nulls is often less than 0.1 mv. Since it is also possible to explore the body surface with a bipolar lead seeking maximum potential difference, these two procedures might be considered in combination as a method for determining the ratio of maximum loop length to maximum width-viewed-edgewise. Quantitative results are very difficult to obtain because the ratio of lengths of image vectors associated with maximum and minimum bipolar leads is usually not known. There are also errors entailed in arriving at the bipolar results of maximum and minimum dipole components since search is weighted by variable and unknown image vectors. Because maximum and minimum bipolar image vectors can easily differ in magnitude by as much as 5:1 (in either direction), depending upon electrode locations, torso shape and dipole location, it is not satisfactory to assume they are roughly equal. It is possible to make estimates of applicable image vector ratios from three-dimensional torso model data if dipole location of the subject is known. Rougher estimates may be made using the image surface for an average dipole location. The entire procedure is less practical than determining the loop ratio by vectorcardiography, especially if a “panoramic” facility is built into the equipment. Indeed, this is one area in which vectorcardiography is a most facile tool.

Conclusions

Characteristics of body-surface potentials produced by planar dipole loops are worth investigation for several reasons: (1) Loops are often found to reside nearly in a plane in practice, (2) previous observations can be unified in terms of a single theory, (3) deeper insight can be obtained into the significance of seemingly unrelated phenomena and (4) ideas for future investigations are influenced by a comprehensive view of these characteristics. The fact that previously observed experimental characteristics (as well as others deliberately sought and found as a result of theoretic predictions) are explainable by a fixed-location dipole hypothesis gives further evidence of its applicability to the human subject. Qualitative determination of the degree to which the dipole loop is confined to a plane is possible with bipolar search lead techniques.
SUMMARIO IN INTERLINGUA

Le characteristicas del potentiales de superficie corporee producite per dipolic ansas planari merita investigation pro plure rationes: 1. In le practica il es trovate frequentemente que le ansas reside in un plano. 2. Previe observationes pote esser unificate in un unic theoria. 3. Le signification de apparentemente disconnectite phenomenos pote esser comprendite plus profundemente. 4. Ideas in re investigationes futur es influentiate per un vista comprehensiva de iste characteristicas.

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Le determination qualitative del grado a que le ansa dipolic es restringite a un plano es possibile per medio de technicas a derivationes bipolar de recerca.

REFERENCES


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