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Near- and Far-Fields: Source Characteristics and the Conducting Medium in Neurophysiology


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Summary: It is possible to appreciate the production of far-field potentials by considering constant current dipolar source voltage distributions in bounded volumes, especially when they are stretched in one direction, e.g., a cylinder. An essentially nondeclining voltage is detected when the recording electrodes are on opposite sides of, and relatively far from, the dipolar source. This voltage maintains its (a) latency, (b) amplitude, (c) morphology, and (d) polarity even if recordings are performed a whole body length away. These four criteria define far-field potentials. A propagating action potential (AP) can be conceptualized as a linear quadrupole or the summation of two dipoles "back-to-back" (+ — — +). The far-field components of the summed dipoles cancel resulting in the anticipated triphasic waveform for APs with only near-field characteristics, not meeting the first three criteria above. Far-field potentials can be transiently generated when any propagating AP constitutes a net “real” or “virtual” dipolar source. “Real” dipolar sources can occur if an AP encounters the termination of excitable tissue, an alteration in conduction velocity, curvature in excitable tissue resulting in a change in propagation direction, or an abrupt change in resistance of the excitable tissue. Virtual dipolar sources may be produced if an AP encounters a change in the size or shape of the extracellular medium or a transition in extracellular conductivity. Key Words: Far-field potentials—Near-field potentials—Volume conduction—Modeling—Bioelectric sources.

Most clinical neurophysiologists feel relatively comfortable observing action potentials (APs) propagate past a pair of recording electrodes and interpreting the detected waveform based on local volume conduction concepts. This feeling of assurance derives from an understanding of an AP's local current distribution and its associated voltage profile, i.e., the AP's near-field. Confusion regarding waveform morphology is likely to arise, however, if an AP encounters either excitable tissue or volume conductor inhomogeneities. Excitable tissue inhomogeneities include termination of excitable tissue (musculotendinous junction, nerve terminal), narrowing and expansion of axonal or muscle fiber diameter (intracellular resistance alteration), or change in excitable tissue direction (curved nerve or muscle fibers). Volume conductor inhomogeneities may include a change in adjoining volume conductor compartment geometry/size, or conductivity. Any of these alterations may lead to production of so-called far-field contributions to the potential field, a phenomenon that may cause uncertainties regarding the clinical interpretation of a waveform’s origin, and thus its clinical significance. Understanding the local current distributions and associated voltage profiles of an AP will help one comprehend the nature of both far-field and near-
field contributions to a recorded potential. In this review, we discuss elucidating examples of far-field phenomena in the literature, provide a general set of definitions and "commandments" with respect to the far-field and address some confusing terminology.

DEFINITIONS

The term far-field potential is taken from antenna theory and first appeared in the clinical neurophysiologic literature describing brainstem auditory evoked potentials (BAEPs) (Jewett and Williston, 1971). As initially described, a far-field potential has characteristics opposite those of a near-field potential. A near-field potential may be defined as a waveform with clear changes in (a) amplitude, (b) polarity, (c) morphology, and usually (d) latency when the active electrode is serially repositioned over small distances. For all near-field recordings, it is assumed that the active electrode is located in close proximity to the bioelectric source of interest. We may, therefore, define a recorded potential as a far-field potential when the above-described four signal characteristics are not influenced by a changing electrode position over small increments. When a far-field potential is generated by a propagating AP encountering one of the above inhomogeneities at a consistent distance from the stimulation site, a constant latency is observed throughout the volume conductor regardless of recording site (Stegeman et al, 1987). The recorded potential at the site of the junction will contain near-field components, which a short distance away become the relatively constant-over-distance detectable far-field potentials. This far-field region of the volume conductor can arbitrarily be defined as the portion in which the potentials decrease < 5% over distances ≈ 10% of the volume conductor's maximal dimension in any direction. Because one of the far-field potential hallmarks is a lack of dependence between waveform latency and electrode position, the term stationary potential (standing wave) is sometimes considered synonymous with far-field potential.

We attempt to reformat the usual discussion regarding near-field and far-field or stationary potentials from one of waveform characteristics to that of unique current source distributions producing particular spatial voltage profile characteristics. Defining current sources and their associated potential field leads to a more intuitive grasp of waveforms recorded in routine clinical practice. As is elucidated, dipolar and linear quadrupolar (also termed tripolar) current sources essentially account for all of the current generators encountered in clinical practice and thus can together be held responsible for all observed waveforms.

DIPOLAR CURRENT SOURCES

Infinite Volume Conductor

The first current source we discuss is the dipole. A dipole consists of two opposite polarity poles, plus and minus (+ -), with current flowing between them setting up an associated voltage profile (Lorente de Nó, 1947; Franssen et al., 1992). If a dipolar current source is located in a homogeneous infinite volume conductor extending in all directions, a characteristic dipolar voltage profile is delineated when an active recording electrode passes across, and in close proximity to, the dipole (Fig. 1A). The potential equidistant

![Figure 1](image-url)

**FIG. 1.** A: Spatial potential profile for a dipolar source in an infinite volume conductor. B: Spatial potential profile for the same dipolar source shown in A, but located in an infinitely long cylindrical volume conductor directed axially. C: Spatial voltage profile along the cylinder's wall as opposed to that measured near to the central axis in B. D: Same dipolar source used in A and B located in a cylinder of finite length with a reference electrode positioned in the dipole's far-field region left of the dipolar source. Note the very flat but non-zero portion of the curve, which is the far-field region. In A–D, the horizontal axis denotes a common arbitrary distance extending to infinity, and the vertical axis denotes identically scaled arbitrary voltages.
between the two poles will, for reasons of symmetry, be assigned as the zero potential. “Potential” must always be defined with respect to a reference value; practically, this reference value is the “indifferent” or G-2 electrode. Of particular importance in the present context is the monotonously decreasing voltage profile at some distance from the two poles directed away from the zero potential point. The voltage rapidly decreases as the distance from either the negative or positive pole increases. The further the electrode is displaced from the current source, the more this rate of voltage decrease slows (Fig. 1A). At infinity, the measured voltage reaches the above-defined zero potential. At the very moment the dipolar source is generated, this spatial voltage profile of decreasing magnitude appears with the speed of light throughout the volume conductor. The spatial voltage profile for a dipolar current source in an infinite volume conductor is a distributed positive-to-negative biphasic potential over distance with voltages that decrease to zero potential at infinity throughout the volume conductor. Because current density in the volume conductor progressively diminishes with distance from the dipole, it will eventually approach zero current. The above-defined zero potential can be found on a plane extending into infinity midway between the two poles. This plane extends into the region where essentially no current flows; one can then follow a path at this large radius all the way around the dipole. Because this is over a zero current pathway, no voltage changes occur, demonstrating the zero potential throughout the far-field region. The above-described dipolar source located in an infinite volume conductor never becomes a constant nonzero. Therefore, dipolar current sources located in an infinite volume conductor cannot produce a measurable, or non-zero, far-field potential (Table 1, commandments I and II).

**Bounded Volume Conductor**

The above-described dipolar current source can now be placed along a cylinder’s central axis with any finite radius, but of infinite length (Fig. 1B). The introduction of the cylinder’s wall or boundary acts to constrain the source’s current from flowing to infinity in all directions, as it cannot flow radially through the nonconductive wall (Fig. 2A) (Dumitru et al., 1993). The current in the vicinity of the dipolar source is also more concentrated than it would be without the boundary because it is precluded from expanding without restrictions. This current flow immediately adjacent to the wall must therefore be tangentially oriented. It is important to understand that in the case of a cylinder, the current between the dipole’s two poles is constrained by the confines of the cylinder’s walls; however, it is free to flow axially out away from the dipolar source. In close proximity to the dipolar source, the current completes a circuit by flowing between the dipole’s positive and negative poles. The current can also flow axially along the cylinder away from the positive pole for any distance and then return in close proximity to the cylinder’s wall crossing the dipolar source and, due to symmetry flow down the cylinder, an equal length away from the negative pole before axially returning to the negative pole, thus completing the “circuit” for this current flow. Therefore, current near the wall is always flowing in the general direction from the positive pole toward the negative pole. With progress longitudinally down the cylinder’s central axis away from the dipolar source’s positive pole, current progressively “peels” away toward the wall to return to the negative pole by adding to this returning current near the wall (Fig. 2A). The returning current along the wall on the cylinder’s negative pole end progressively peels away toward the central axis to return to the negative pole. The “peeling off” process results in a

<table>
<thead>
<tr>
<th>Table 1. “Ten commandments” of far-field potential generation</th>
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<tbody>
<tr>
<td>I. In an infinite volume conductor, a dipolar source cannot produce a far-field potential, nor can any other type of current source.</td>
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<tr>
<td>II. A dipolar source located in a finite volume conductor can produce a non-zero relatively constant potential difference over distance, i.e., the far-field potential.</td>
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<td>III. A far-field potential can best be observed when recordings are made in a finite volume conductor that is stretched in one direction, i.e., long and thin.</td>
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<td>IV. Far-field potentials can be generated by the peripheral neuromuscular system.</td>
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<tr>
<td>V. A far-field potential can be detected only when the recording electrodes are far from and on opposite sides of the dipolar source.</td>
</tr>
<tr>
<td>VI. An impulse propagating along excitable tissue of sufficient length to contain the entire impulse lacks a dipole component and does not produce a far-field distribution by itself.</td>
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<tr>
<td>VII. Any disturbance in the constant propagation of an impulse along excitable tissue, including directional changes and anatomic alterations in the fiber’s surroundings, will generate a dipolar potential field and lead to far-field potentials.</td>
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<tr>
<td>VIII. Propagating impulses can induce transient dipolar sources only at sites of fixed anatomic transitions, implying that the dipolar fields are not propagating; i.e., dipolar fields are nonmoving or stationary.</td>
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<tr>
<td>IX. Balanced quadripolar sources only have near-fields, but dipolar sources have both near-fields and far-fields.</td>
</tr>
<tr>
<td>X. A far-field potential can never be recorded with a bipolar montage using a short interelectrode distance.</td>
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</table>
A dipolar current source is located along an infinitely long cylinder's central axis. Note how the current flows from the positive to negative pole (dashed lines with arrows indicate current flow direction). In the immediate vicinity of the dipolar source, small circular current flow patterns are described. At sites more distant from the dipole, the current extends from the positive pole along the central axis and then "peels" away and turns toward the cylinder's wall. This current flow then continues to the cylinder's opposite end to return along the central axis, completing the circuit at the dipole's negative pole. This situation continues along the cylinder's radius "demarcating" two regions with equal cross-sectional area. An inner cylindrical region is demarcated from an outer equal volume "doughnut" region by this first set of "demarcating isopotential" lines (Fig. 2A). This results in the effective resistance per unit distance for current flowing away from the dipole to be equal to that of the returning current flow toward the dipoles. Those isopotentials in the outer doughnut volume start from a region between the two dipoles and always terminate perpendicular to the cylinder's wall. The magnitude of these isopotential lines in between our defined zero potential (half-way between the positive and negative poles), and the demarcating isopotential asymptotically approach the demarcating potential's magnitude. A second set of isopotential lines are essentially "ellipsoid shaped" between the demarcating isopotential lines (inner circular cross-sectional volume). Their magnitude is high near the dipoles and rapidly decreases with distance from the dipoles approaching but again, never reaching, the demarcating isopotential's value.

The above example reflects the theoretical situation in regard to dipolar sources and cylindrical volume conductors. There are practical limitations imposed on this theoretical explanation which require discussion. Possibly the most important limitation is that of the neurophysiologic instrument's ability to measure vanishingly small potential differences associated with the decreasing current density with increasing distance from the dipole source. In experiments attempting to define the beginning of the "far-field" region, instrumentation limitations have documented the initiation of an isopotential (far-field) region at ~1.5 and ~1.9 times the cylinder's radius when measurements are made along the wall and central axis, respectively (Fig. 2B) (Stegeman et al., 1987; Dumitru et al., 1993). These limits are obviously arbitrary and depend directly on the amplifier sensitivity of the instrument. For practical measurement purposes, the above-noted radial ratio limitations essentially define a far-field region, i.e., where no potential difference (<5% percent of the total non-zero potential) can practically be detected over large distances (Table 1, commandment II).
Measurements made in clinical neurophysiology are not performed in infinitely long cylinders. Most clinical measurements are made in finite cylinder-like volumes, such as arms, legs, torso, and neck. The introduction of a finite cylinder means that it is not feasible to locate a reference electrode at a zero point as in Fig. 1A or at infinity, and the effects a reference electrode has on the recorded waveform cannot be conveniently ignored. If the reference electrode is positioned at some location distant from the dipole generator, it is likely to be in the dipole’s far-field region (Fig. 1D). This means that no far-field potential will be detected when the active electrode is also in that far-field region. Sweeping the active electrode past the dipolar source records a voltage profile similar to that of an infinite cylinder (Fig. 1B) with a far-field potential on the other side of the source (Fig. 1D). In circumstances such as that shown in Fig. 1D, the terms active and reference are meaningless, which is why some investigators studying far-field potentials prefer the terms E-1 or G-1 and E-2 or G-2 to replace “active” and “reference,” respectively (Dumitru and Jewett, 1993).

When the active recording electrode is located on the side opposite the dipolar source from which it first began taking measurements, a region is reached where there is no longer a decrease in potential magnitude (Fig. 1D; Table 1, commandment V). The measured potential remains constant in terms of latency, amplitude, and polarity, i.e., a far-field potential. The region of the volume conductor in which there is no potential detected or in which a constant potential is detected defines the beginning of the dipolar current source’s far-field region. It can be demonstrated that relatively distinct zones exist for a current source between the so-called near-field and far-field. Clearly two closely spaced electrodes (bipolar recording montage) cannot measure a far-field potential since only a zero potential will be recorded in the far-field zone. The above-described method of establishing near-field and far-field regions should reduce ambiguity about the clinical distinction between near-field and far-field volume conductor regions.

Spherical Volume Conductor

Locating a dipolar current source in a sphere or its planar equivalent (circular volume conductor) discloses an interesting relationship between the active electrode’s location and the potential recorded (Fig. 3) (Nunez, 1981; Jewett et al., 1990; Dumitru and King, 1992b). If a reference electrode is located at the dipole’s midpoint defined as the zero potential line and the active electrode is positioned sequentially along any radius beginning at three times the interdipolar spacing from the sphere’s center to its wall, there is a continual decrease in the amplitude of the recorded waveform. This decrease essentially follows an inverse square relationship, although it flattens to a non-zero value near the sphere’s wall (Fig. 3A). This value is
three times that otherwise predicted for such a radius in an unbounded infinite volume and has <5% change from 80% of the radius to the sphere's wall (Nunez, 1981; Dumitru and King, 1992b). Rotating the recording electrode about the sphere's center for any given radial distance, however, discloses a change in the magnitude of the recorded waveform that follows a cosine function (Fig. 3B). The cosine function is flat near 0° or 180°, in line with the dipole's axis, where a change of <5% amplitude occurs over 36° (±18°) at each end of the sphere. The volume in which the dipole potential is relatively constant in amplitude is much more restricted in a sphere than in the arbitrarily long cylinder and conforms to the outer regions of two cones extending 18° above and below the dipole axis (Fig. 3C). It is only this outer 20% of the radius of two 36° cones on opposite sides of the dipole's axis that conform to this relatively constant potential over distance, forming what may be considered the sphere's far-field region. Therefore, the sphere's far-field region is unlike that observed in the cylinder because the cylinder's length may be increased without a change occurring in the far-field potential. In the sphere, increasing its radius results in a decrease in the magnitude of the far-field potential by an inverse square function within the above-defined far-field zone (Table 1, commandment III).

QUADRIPOLAR (TRIPOLAR) CURRENT SOURCES

A propagating AP gives rise to a so-called quadrupolar current source (Plonsey, 1969; Stegeman et al., 1979). The quadrupole can be conceptualized as consisting of two dipoles oriented “back-to-back” so that the two negative poles of each dipole are adjacent (+−−+) or, more appropriately, superimposed (+==). When the two dipolar sources are depicted in the “superimposed” fashion, an equivalent description is that of a tripole (+−−). For the purposes of this discussion, a quadrupolar source is utilized where the two dipoles are sequentially aligned. This is the so-called leading/trailing dipole (L/TD) model, which lends itself nicely to conceptualizing the relationship between dipolar/quadrupolar sources and their interactions with finite volume conductors (Deupree and Jewett, 1988; Jewett, 1990; Dumitru and Jewett, 1993).

Finite Volume Conductors

Cylindrical Volume Conductors

For the purposes of this discussion, an infinite volume conductor for quadrupolar sources is not consid-
tive spike (Fig. 4C). This waveform is the familiar triphasic AP recorded for a propagating nerve or muscle action potential.

The initial and trailing positive spikes begin from and return to the zero voltage level (Fig. 4C). This is quite different from each of the subcomponent dipolar current sources in a cylindrical volume conductor. A dipolar source generates a far-field potential of opposite polarity but equal magnitude on either side of its poles (Figs. 1B and 4A and B). When the two dipoles are superimposed in the manner described, the far-field potentials of opposite polarity summate to cancel each other. Therefore, quadrupolar sources consisting of equal dipolar sources cannot generate far-field potentials because the respective dipolar far-field components cancel each other, yielding only a triphasic near-field extracellular recorded potential. Therefore, APs propagating along a uniform segment of excitable tissue generate near-field but not far-field distributions.

The above description of balanced dipoles forming a quadrupolar source begs the question of what would happen if one of the dipoles were altered in such a way that it no longer equaled its dipolar counterpart. Although an AP may be conceptualized as consisting of two dipoles of equal strength, the two dipoles are not identical from the perspective of their dipolar lengths or individual current density profiles. Specifically, the segments of a nerve or muscle fiber containing a depolarization phase of an AP is considerably shorter than that which maintains the repolarization phase. Similarly, the current distributions for depolarization/repolarization are also different. It is appropriate to express the dipoles in terms of their dipolar moments, which are simply defined as the dipolar current strength multiplied by the distance of separation between the dipole's equivalent two poles. The AP is characterized by stating that the leading dipole moment exactly balances the trailing dipole moment. This occurs because the leading dipole is shorter but has greater current density than the trailing dipole. Physically, this dipole moment balance is related to the fact that intracellularly the AP is initiated and ends at the same transmembrane potential level. It is to be expected that an AP propagating along a segment of excitable tissue long enough to encompass the entire AP should behave as a balanced quadrupolar source, as described above, from the perspective of the leading and trailing dipole moments. As long as the leading and trailing dipole moments are equal, no far-field potentials are generated (Table 1, commandment VI).

It is also to be anticipated that should either of the leading or trailing dipolar moments of the AP change, creating an unbalanced quadrupole, a resulting "net" dipolar source is produced (Fig. 5). A dipolar source in a cylindrical volume conductor generates a far-field potential distribution in addition to its near-field potential distribution. The near-field waveform may still have an appearance similar to that recorded before the dipolar moment alteration (e.g., triphasic), but a potential is now detected in the far-field regions of the cylindrical volume conductor (Fig. 5C). Therefore, upon any alteration in an AP such that the leading or trailing dipolar moments are no longer balanced and do not cancel each other in the far-field, a net dipolar current source is generated with an associated far-field potential (Table 1, commandment VII).

Once the cylindrical volume conductor's far-field region is reached, it truly does not matter what further shape the volume conductor has with respect to re-
cording the far-field potential. For example, if a spherical volume conductor is attached to the end of the above-described cylindrical volume conductor at some point beyond the establishment of the far-field potential, the entire sphere will assume the same voltage as that portion of the cylinder that has the far-field potential. The sphere may be replaced with any other desired shape (e.g., the torso at the end of an arm), and the contained volume will continue to have the same far-field voltage as the cylinder. Again, this occurs because a vanishingly small current is flowing in the far-field region and any volume attached will therefore simply assume the same measurable voltage as that in the far-field; i.e., it will be equipotential with the far-field potential.

Spherical Volume Conductors

Quadripolar sources consisting of balanced dipolar moments do not generate measurable far-field potentials. This statement applies equally to cylindrical and spherical volume conductors. If circumstances arise in which a dipolar moment imbalance occurs within a spherical volume conductor, a net dipolar source is generated. A potential difference with a far distant reference electrode can then be detected where none existed for the balanced quadrupole. This potential fulfills far-field potential criteria in the spheres' segments described previously (see section on Bounded Volume Conductor: Spherical Volume Conductor).

FAR-FIELD AND BRAINSTEM AUDITORY EVOKED POTENTIALS

An obvious association to the phenomenon of a far-field is that of a source generating potential differences that can be detected by electrodes located a large distance away. Because the brainstem sources of the brainstem auditory evoked potential (BAEP) indeed have a deep location in the head, no conceptual problems arose with the initial terminology "far-field potentials" (Jewett and Williston, 1971). Nevertheless, amplitude changes are observed in BAEP as a function of electrode position about the cranial surface. Actually, most BAEP obey only far-field potential criteria c and d as defined previously. Many BAEP, although probably generated by nonpropagating dipolar sources (Martin et al., 1995), cannot therefore be considered a far-field potential as defined above, i.e., no changes in all of the aspects (far-field criteria a–d) with different electrode position over the entire scalp. BAEP may be recorded unaltered in latency, amplitude, and morphology only over restricted areas (the far-field region in spheres as described above).

FAR-FIELD AND SOMATOSENSORY EVOKED POTENTIALS (SSEP)

The discussion concerning far-field potentials attracted further interest because of observations of far-field components in somatosensory evoked potential (SSEP) experiments (Cracco and Cracco, 1976). Because so-called " noncephalic" reference electrodes (knee, contralateral hand) were used, Cracco and Cracco recorded median nerve SSEP components with a shorter latency than had been previously described (Fig. 6). The early peaks were denoted as P9 and P11 according to their positive polarity and typical latency in milliseconds after stimulation of the wrist. These components can be measured all over the skull with little if any change in wave shape, amplitude, or latency. The P9 potential was intensively discussed in the ensuing years with respect to its source (9-ms latency), obviously somewhere in the peripheral nervous system. Bioelectric activity from the nervous system measurable over such long distances (in the order of the dimensions of the body) did not, and still does not, fit into the intuitive perception of such signals.

With ongoing research, new SSEP far-field components and properties were discovered (Yamada et al., 1985). In particular, it was demonstrated that after electrical stimulation of the median nerve at the wrist six to seven components (including the above P9 component), all with their origin somewhere on the route between wrist and brainstem, can be measured (Fig. 7) (Kameyama et al., 1988). The peaks have latencies approximating 3, 4 (not evident in Fig., 6, 9, 11, 13, and 14 ms. From the latencies of the four earliest peaks, one can conclude that they originate in the peripheral nervous system from the passage of the median nerve AP volley along the elbow, the distal part of the biceps brachii muscle, the deltoid muscle, and along the axilla and Erb's point.

FAR-FIELD AND PERIPHERAL NERVE/MUSCLE CONDUCTION

That the source of a propagating nerve or muscle AP effectively has no net dipole component (Rosenfalck, 1969; Plonsey, 1974; Stegeman et al., 1979) is in concordance with the observation that a propagating nerve or muscle impulse cannot be recorded beyond a distance of a few millimeters—to a few centimeters at most—from the current source. As already described,
FIG. 6. Early somatosensory evoked potentials components after median nerve stimulation at the wrist measured with a reference electrode on the contralateral hand (H). The “active” electrode is placed on the midcentral head (C7), the right ear (A2) is placed just over the neck (inion) and just above the nose (nasion). The lowest trace is a recording made close to Erb’s point. (Reproduced with permission from Cracco and Cracco, 1976.)

a propagating AP can be conceptualized as a balanced quadrupolar source that is incapable of generating far-field potentials (Table 1, commandment VI).

One may reasonably question why far-field phenomena are present in the peripheral neuromuscular system where all bioelectric activity appears to be of a quadrupolar traveling nature. This very question has provoked considerable interest in far-field potential generation. Theoretical (Stegeman et al., 1987) and experimental (Deupree and Jewett, 1988; Dumitru and King, 1993; Kimura et al., 1984; Kimura and Yamada, 1990; Sohmer, 1991) studies disclosed several causes for the generation of far-field potential distributions in the peripheral neuromuscular system. When the constant propagation of a quadrupolar AP in a cylinderlike volume (e.g., upper/lower limb or torso) is disturbed in some way, dipolar sources, and consequently far-field potentials, are generated.

Several AP “disturbances” have been proposed or are documented to result in far-field potentials secondary to the formation of dipolar sources. Causes that evoke “real” dipolar sources include: (a) generation or blocking of a propagating AP, (b) alteration in impulse conduction velocity, (c) curvature in a nerve or muscle fiber producing a change in AP propagation direction, and (d) abrupt change in excitable tissue diameter or intracellular resistance. The term “real” is defined so that the AP itself is affected and thus changed by the imposed condition or disturbance. So-called “virtual” dipolar sources may occur secondary to a propagating AP encountering (a) a morphologic change (size or shape) in the extracellular medium, or (b) transitions in the conductivity of the extracellular medium. In this sense, the word virtual is used to suggest that the current source has not been directly affected, but that the surrounding medium has changed in some manner which in turn produces an imbalance between the potential distribution resulting from the leading and trailing dipoles of the AP (Stegeman et al., 1987; Dumitru and King, 1993).
Rt. median nerve stimulation
reference: knee

FIG. 7. Six far-field components denoted N3, N6, N9/P9, P11, P13, and P14 are recorded on the pathway between wrist and brainstem. Stimulation was at the right median nerve at the wrist. The reference electrode was placed at the knee. The lower seven traces were recorded with an interelectrode spacing of 5 cm along the right arm. (Reproduced with permission from Kameyama et al., 1988).

The above conditions affect the propagating AP by adding to its pure quadripolar source character a net dipolar source. Potential distributions caused by such a dipole source do appear during the passage of an AP along the disturbing site and disappear after the passage. The passage of the disturbance, and thus, the far-field appearance, lasts only a few milliseconds at most, i.e., the duration of the AP across the fixed "disturbance." This is exactly what is observed for the above-described early SSEP components. The potential field is monophasic as a function of time, with a polarity dictated by the type and direction of change and is also determined by the location of both recording electrodes (Dumitru and King, 1993; Stegeman et al., 1987). Properties of the two source types are summarized in Table 2. An earlier opinion that all far-field potentials should be of positive polarity, as noted for the first SSEP far-fields (Desmedt and Nguyen, 1984), is based on a misconception regarding the origin of a far-field and contradicted by the recording of consistent negative far-field potentials (e.g., P9 vs. N9 component, Fig. 7). Far-field potential polarity is primarily dependent on the transiently induced net dipole's polarity with respect to the recording electrodes. It is clearly established that propagating action potentials can induce transient dipolar fields and hence far-field potentials when the above described "real" and "virtual" dipolar source conditions occur. As is true for all dipoles, in connection with a suitable volume conductor, these sources can induce far-field distributions, just as they also produce near-fields. Therefore, it is important to realize that dipolar sources have both near-field and far-field components while balanced quadripolar sources only have near-field distributions. All of the above causes by which a dipole is generated refer to fixed anatomical positions. This is the reason why it is often preferable to use the terms non-moving and moving instead of using far- versus near-field. In Table 2 this property is the only one distinguishing the dipole and the quadrupole field in all circumstances; i.e., real or virtual. (Table 1; commandment VIII).

Motor Unit AP Termination:
A 'Real' Dipole Source

A rather straightforward example in which the leading/trailing dipole concept is illustrated is found in motor unit AP as measured at the skin surface. When potential measurements are made along the longitudinal direction of a fiber, single motor unit activity can be isolated after triggered-averaging of the signal by use of an intramuscular needle electrode. An example of such a registration with 16 electrodes in a row along the human biceps brachii muscle can be documented (Fig. 8) (Stegeman, 1996; Stegeman et al., 1996). The waveforms are clearly composed of two main components: a propagating and a nonpropagating component. The negative spike reflects the traveling muscle fiber impulses along the sarcolemma from the endplate (Fig.)
TABLE 2. Characteristics of dipolar/quadrupolar sources in electrophysiology

<table>
<thead>
<tr>
<th>Property</th>
<th>Dipole</th>
<th>Quadrupole</th>
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<tbody>
<tr>
<td>Real</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Virtual</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Propagation (changing latency)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Near-fields (changing amplitude at the same time over different electrodes)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Far-fields (constant amplitude at the same time over different electrodes)</td>
<td>Yes, in finite conductors; more easily seen when stretched as in a cylinder</td>
<td>No, if balanced</td>
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</table>

8, at the seventh trace) in two directions until both tendon areas are reached. In the lower eight traces (Fig. 8), the traveling component shows two peaks, apparently because the motor end-plate area consists of two distinct subcomponent regions. The downward positive nonpropagating component at the end of the traces clearly represents a nonmoving potential field with an associated near-field in the first three traces and a far-field in the rest of the traces. This example clarifies why the terms near-field and far-field may not always be ideal in making a distinction between potential components with different sources. This example explains why it is more appropriate to consider terms such as moving and nonmoving (stationary) to define different subcomponent sources better.

The generation and time envelope of a true net dipolar source at the fiber end is shown schematically in Fig. 9. Five spatial (vertical) profiles of the location for a traveling leading (L) and trailing (T) dipole complex of a muscle fiber AP are outlined for five moments in time (horizontal). In the first trace in Fig. 9, both dipoles are traveling and are equally strong. No far-field potential is measured (Voltage [V] = zero). In the second trace in Fig. 9, dipole L has encountered the fiber’s termination and subsequently decreases in

![FIG. 8. Measurement of the spatiotemporal potential profile along the skin surface of a motor unit of the biceps brachii muscle. An array of 16 surface electrodes is located in parallel with the main direction of the fibers of the muscle. The distal part of the arm is in an upward direction. The reference electrode for all signals was placed on the ipsilateral elbow. The profile is obtained after triggered-averaging with an intramuscular needle to trigger the motor unit firing pattern. The location of the motor end-plate zone and the transition from muscle fibers to tendon are indicated schematically as deduced from the character of the signal components. Negative potential values are plotted downward. Note the propagating character of the main negative (upward) peak of this motor unit action potential in two directions, starting at the end-plate region, and the nonmoving positive potential peaks at all locations (Reprinted with permission from Slegeman et al., 1996).](image)

![FIG. 9. Schematic of five spatial profiles of the location of the traveling leading (L) and trailing (T) dipole complex of a muscle fiber impulse for five moments in time around the blocking of the action potential at the fiber–tendon transition. The arbitrary (far-field) potentials as measured between the dots left and right of the profiles are indicated (Voltage [V]: 0, ½, 1, ½, 0) (see Fig. 8).](image)
magnitude. Dipole T becomes dominant and an effective dipole source (+ -) appears. A far-field is recorded across the terminating muscle AP (V = ½). In the third trace in Fig. 9, dipole L has completely disappeared and the far-field potential magnitude reaches its maximum since dipole T still is completely active (V = 1). In the fourth trace, dipole T also decreases, and the far-field potential magnitude decreases again (V = ½). The fifth trace denotes the trivial situation after the disappearance of both dipoles (V = zero). The polarity of the far-field recording (here positive) (Fig. 9) is not changing as a function of time in accordance with the monophasic appearance of the nonmoving potential component in Fig. 8. Documentation of muscle far-field potential generation and model calculations of end potentials is available in the literature (Gydikov and Kosarov, 1973; Dumitru and King, 1991; Dumitru and King, 1992a; Gootzen et al., 1992).

HAND MODEL: A VIRTUAL DIPOLE SOURCE

A very important contribution to an understanding of far-field generation was provided by Kimura et al. (1984), who published an illustrative physiological human hand model for generation of virtual dipolar fields. The model refers to a change in the size or shape of a volume conductor through which an AP propagates. It was demonstrated that dipoles are generated at anatomic transitions at the hand (wrist to palm, palm to finger) when the antidromic median/ulnar sensory nerve AP propagates along these transitions sites. A term sometimes used for such a dipole field caused by anatomic changes is "junctional potential" or "boundary potential." Its mechanism is less easy to explain than that of a true real dipole. However, the leading/trailing dipole concept is helpful. The leading dipole of a traveling tripole enters a region with deviant extracellular properties, which effectively leads to a change in the extracellular resistance per unit length in the fiber's direction. The leading and trailing dipolar components of the AP act as constant current sources (Heringa et al., 1989). The extracellular potential generated by the leading dipole differs from the potential generated by the trailing dipole which is still in another part of the extracellular medium with different resistance characteristics. Effectively, but without a concrete physical change in the AP current source, the leading and far-field potentials of the leading and trailing dipoles no longer cancel, yielding a dipole potential field generated in the extracellular space. Simulation and experimental studies have validated this explanation (Stegeman et al., 1987; Dumitru and King, 1993). After some time, the trailing dipole also enters the new environment and the extracellular impedance mismatch disappears, resulting again in a balanced quadrupole. A referential recording compared with bipolar antidromic sensory median nerve recording can dem-

![Hand model diagram and traces](image_url)
protrude this point (Fig. 10) (Spaans, 1984). This example is very clear because motor activity is absent in a patient with hand muscle paralysis. A clear positive (downward) far-field component is shown in the curves 2-4 and 3-4 in Fig. 10. From the latency of this component, one can conclude that indeed a virtual dipole at the transition between palm and third finger is responsible for production of the observed far-field potential. The leading dipole of the nerve AP volley first enters the smaller cylindrical finger and encounters greater extracellular resistance there. The potential over this resistance is greater than the potential with opposite polarity generated by the trailing dipole still in the palm area surrounded by a greater volume and less resistance. The traveling impulse can be recognized by comparing the negative (upward) components in traces 1-4, 2-4, and 3-4 in Fig. 10. The bipolar trace 2-3 in Fig. 10 shows that the nonmoving effect is of a far-field nature. As already described, a bipolar recording with both electrodes in the same far-field region fails to detect a far-field potential, as demonstrated by trace 2-3 in Fig. 10 (Table 1, commandment X).

CONCLUSION

The subject of far-field potentials and their production occasionally even conjures the association of magic or mysticism. It is becoming more clear, however, that far-fields or, more appropriately, dipolar source potential fields are detected at numerous sites in the neuromuscular system. Actually, dipolar fields are common in central nervous system signals; however, the volume conductor is not large enough to fully express a far-field from many dipolar sources. Far-fields have been shown to be a subset of potential fields caused by dipolar sources. Dipolar sources can be "real," as is illustrated in the effect of an AP potential encountering excitable tissue termination, or "virtual" due to the surrounding medium, as is illustrated in the described hand model. The P3, SEP component is an example of a virtual dipole field, apparently set up by the volume conductor transition between arm and thorax, i.e., in or about the axilla or brachial plexus. Of importance is that nonmoving dipolar and moving linear quadrupolar (tripolar) sources are the two fundamental building blocks of all neurophysiologic recordings. Any waveform characteristic represents the activity of a combination of these two source types. This insight provides a more intuitive understanding of a wide range of different waveforms; i.e., it is important to remember that dipolar sources do not propagate, that quadrupolar sources cannot be of a virtual character, and that a balanced quadripolar traveling source does not evoke a far-field potential.

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REFERENCES


