The recording characteristics of the monopolar needle in three dimensions have not been well established. A simple spherical recording territory is commonly assumed with the very tip proposed to have a greater spatial recording sensitivity by some authors. We demonstrate by enlarged physical modeling in a homogeneous volume conductor that the recorded amplitude diminishes more gradually radially away from the conical surface than distally past the tip or proximal to the insulation edge. The sensitivity over the exposed metallic surface is found to be uniformly proportional to the area, which results in relatively less sensitivity at the tip than the middle and proximal portions of the conical recording surface. The overall spatial amplitude recording characteristics can be better described by an apple shape than a sphere, centered at the midportion of the exposed conical surface. A better appreciation of the actual spatial recording characteristics of the monopolar needle electrode can result in more accurate physiologic interpretations of quantitative motor unit analysis. © 1996 John Wiley & Sons, Inc.

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MONOPOLAR NEEDLE ELECTRODE SPATIAL RECORDING CHARACTERISTICS

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The monopolar needle electrode was first introduced in 1949 by Jasper and Ballem.[7] Over the ensuing years this electrode has surpassed the popularity of concentric needle electrodes and is now the most popular needle electrode sold by most manufacturers in the United States (personal communication with major electrode manufacturers). Despite its widespread use in clinical practice, little research has been performed to understand this electrode's recording characteristics in a volume conductor.[8] It has been assumed to have a spherical recording territory.[2,11]

A single study has modeled the monopolar needle's recording characteristics and assumed a spherical recording territory.[8] Additionally, it was proposed that the needle's conical tip records significantly larger potentials than the more proximally located exposed surface. In essence, the tip was assumed to have a greater weighting function than the remainder of the exposed metallic cone's recording surface. The net effect is to suggest that the monopolar needle electrode performs a spatially selective recording because the tip preferentially contributes to the recorded potential.[8]

Concentric and single fiber needle electrodes, however, have been the focus of several investigations, yet a consensus regarding these electrodes' recording characteristics does not exist.[5,6,9,12] It has been postulated that the concentric needle's cannula may act to shield one half of the electrical activity in the vicinity opposite the recording surface.[9] The net result would be a hemispherical recording territory. Recent publications call into question this assumption and suggest that bioelectric activity in the previously assumed noncontributory "shielded" hemisphere may contribute to the recorded potential.[6,12]

A concentric needle electrode has a comparatively smaller exposed active recording ellipsoidal area, 0.07 mm^2, than the 0.24 mm^2 for the conical monopolar needle's exposed surface area.[2,8] The finding of similar motor unit action potential durations[2] whether recording from a monopolar or concentric needle electrode would appear to substantiate a selective tip influence. Recording primarily at the

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tip of the monopolar electrode would make the "active" recording surface areas and, therefore, the relative territory of a volume conductor observed much more comparable between the monopolar and concentric needle electrodes. This in turn would allow a similar motor unit territory to be recorded, resulting in similar motor unit action potential durations.

Selective recording at the tip is not, however, supported by the common anecdotal clinical experience that individual waveforms are observed to persist unchanged despite slight movements (much greater than 1/10 of the tip length, which should be on the order of 70 μm or less[8]) on insertion of the monopolar electrode in tissue. Selective recording at the tip should not allow waveform persistence with any movements greater than the tip's small dimensions. The finding of reduced amplitudes when the Teflon® coating peels, allowing twice the original recording surface area, also does not favor selective recording confined to the very tip.[1]

This investigation attempts to better define the recording characteristics of a monopolar needle electrode in a volume conductor, i.e., its spatial weighting function. Electrode weighting functions are not generally uniform along the recording surface, but depend upon recording surface geometry and have directional sensitivity.[6] In this study, a monopolar needle electrode is physically modeled by an enlarged scaled conical recording surface in a homogeneous volume conductor. If the metallic tip preferentially records the generated potential, then the overall monopolar recorded potential will more closely approximate the potential measured in this region than that averaged over other areas of the exposed surface. Preferential weighting near the tip compared to a uniform weighting function throughout the surface of this monopolar model is tested. Likewise, if preferential weighting of a certain portion of the monopolar electrode occurs, then a greater recorded potential is expected when a constant dipolar point surface is near the preferential area as compared to other portions of the exposed surface. The sensitivity of the monopolar needle electrode model to various positions of a constant dipolar point stimulation source is also investigated.

MATERIALS AND METHODS

A commercially available monopolar needle electrode (DMF 25, TECA Corp., Pleasantville, NY) served as the template for all constructed physical models. A photomicrograph of the recording tip permitted analysis of the necessary dimensions regarding shaft diameter, Teflon® coverage, conical tip shape, and angular pitch of the needle tip's taper. Twenty DMF monopolar electrodes, five randomly acquired from four lots, were analyzed microscopically to determine the exposed metallic tip to total taper length ratio. The mean ratio was found to be 0.38 ± 0.08 (standard deviation) with a range of 0.28–0.54. Enlarged physical models were constructed to proportionately match the dimensions and taper as determined by the photomicrographic analysis.

Three monopolar needle models were fabricated out of stainless steel with shaft diameters of 5.0, 2.5, and 1.25 cm. These represent scaling of 1 cm to 100 μm, 200 μm, and 400 μm, respectively. The conical taper of these models matched the commercially available monopolar needle's conical tip. All exposed metal was covered with a nonconducting material (DEM-KOTE® epoxy insulating varnish, Sherwin-Williams Co., Bedford Heights, OH) except the distal aspect of the conical surface. The amount of exposed metal was 0.38 times the length of the taper, which matched the above microscopic analysis.

A glass container with a diameter of 55 cm and height of 59 cm held normal saline as the volume conductor in which all investigations were performed. The glass container was filled to a height of 42 cm with sterile 0.9% saline solution. Each modeled monopolar needle was vertically and centrally positioned from above so that the tip was at the mid depth (21 cm) of the normal saline volume conductor. The axis of the needle model was aligned with the central axis of the volume container to obtain symmetry. This modeled electrode formed the active input for subsequent monopolar response recordings. The reference input came from a 2.5-cm stainless steel disk located at the container's periphery at the same depth as the monopolar model's tip in the volume conductor. A similar electrode served as common ground and was located along the opposite side of the container at a comparable depth in the volume conductor.

A cathode/anode stimulating pair from which our monopolar model electrode measured a response was constructed to be a constant dipolar point source with a very short distance between the cathode and anode. The cathode consisted of a platinum/iridium subcutaneous electroencephalographic needle (Grass Corp., Quincy, MA) positioned 1.5 cm within and from the tip of a normal saline filled Nalgene™ (Nalge Co., Rochester, NY) polyvinyl chloride clear tube of 0.5 cm/0.3 cm outside/inside diameters, respectively. A 3-mm-wide strip of aluminum metal surrounded the tip of the Nalgene™ tube and acted as a circumferential anode. A bipolar square wave constant current wave form of ±4 mA amplitude was delivered through the cathode/anode stimulating electrode pair at 35 Hz, produced by an arbitrary waveform generator (Model 75A, Wavetek Instruments Division, San Diego, CA). Responses from this cathode/anode stimulating pair were averaged 20 times and verified three times for consistency by a TECA Sapphire Premier electrophysiologic instrument (TECA Corp., Pleasantville, NY).

Monopolar Electrode Surface Sensitivity. The cathode/anode pair was positioned below the monopolar model's tip and aligned such that the anodal aluminum ring was centered to the monopolar model's central axis (Fig. 1A). This anodal ring could be positioned at any distance from 0 to 4 cm from the tip. For this portion of the investigation only the 5-cm-diameter monopolar electrode model was used. An apparatus was constructed that allowed additional measurements within the volume conductor at 1 mm perpendicular distance from the surface of the monopolar model's exposed metal (Fig. 1A and B). The active electrode for these measurements was a platinum iridium subcutaneous electroencephalographic needle (Grass Corp., Quincy, MA) modified to be 1 mm long. A 0.5-mm-diameter rigid nonconductive stop ensured the 1-mm spacing from the surface of the monopolar model to the tip of the recording electrode.

Recordings were made along one vertical line along the side of the conical metallic surface every 2 mm starting at 1 mm from the tip. Due to cylindrical symmetry with the cathode/anode stimulating pair and volume conductor, the potentials recorded along one aspect of the edge from distal to proximal apply to the entire circumference of the monopolar model at that distance from the tip. The surface area of these 2-mm strips increases as one moves proximally away from the monopolar needle's tip due to its conical shape. The recorded potentials along the edge, multiplied by the amount of surface area for that strip, was summed for all 2-mm positions and then divided by the overall surface area to provide a uniform area weighting with which to compare our actual monopolar recorded potential from the model as a whole.

A transition occurs at 7.5 mm along the edge from the tip, where the taper shifts from 19° to 7.5°, thereby approximating the rounding of actual monopolar

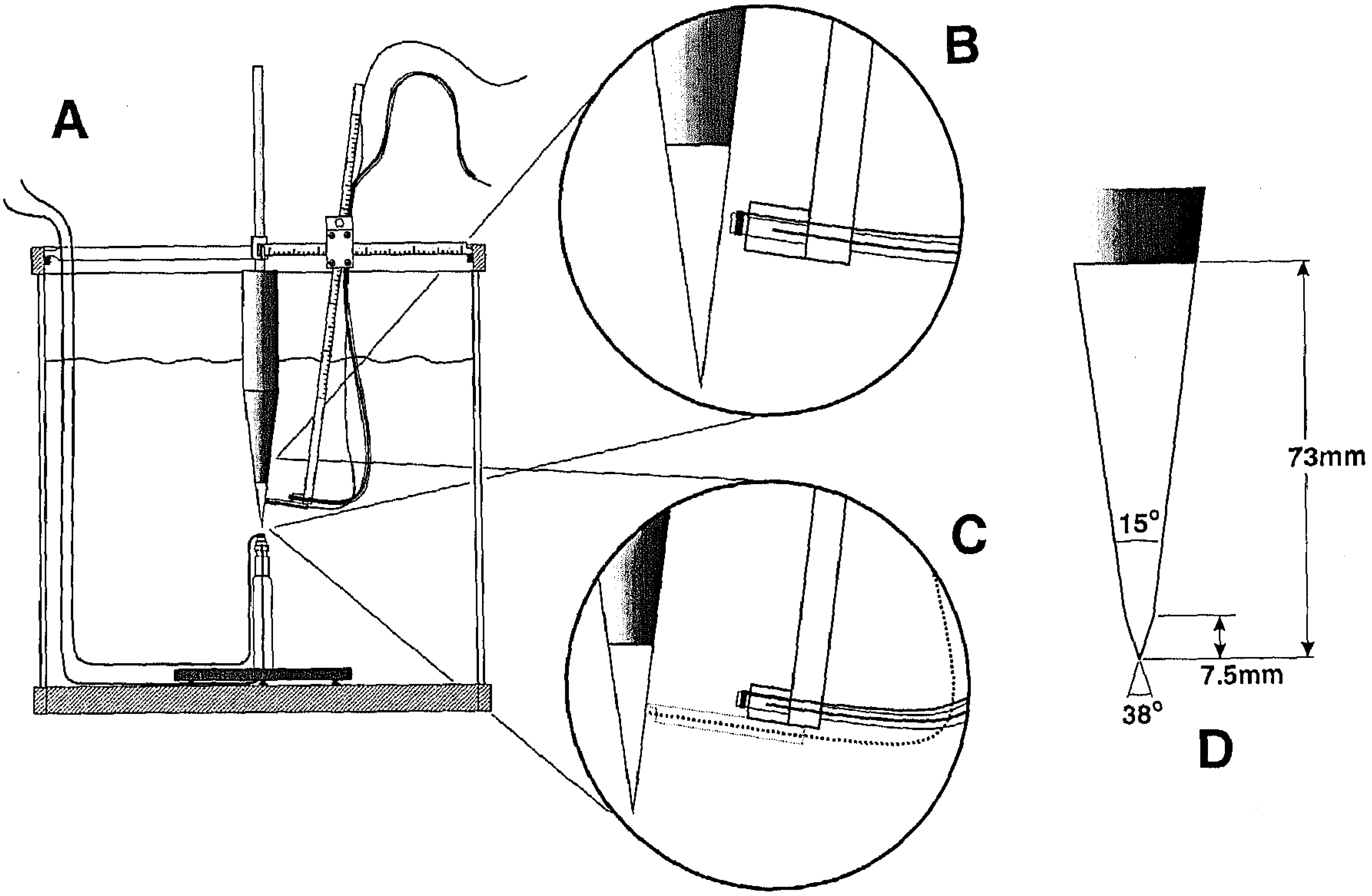


FIGURE 1. (A) Experimental apparatus for analysis of monopolar electrode surface sensitivity and electrode current shunting effects. The measurement of potentials over the surface area is compared to the monopolar model's recorded response as a whole. The distance from the monopolar model's tip to the symmetrically located stimulating tower's anodal ring below could be varied from 0 to 4 cm. (B) Inset showing the anode/cathode stimulation Nalgene™ tubing apparatus which was freely positioned thoughout one hemiplane for analysis of monopolar spatial response. (C) Inset illustrating the added nonconductive stop (small dotted lines) used to position the new active electrode (dashed lines) 1 mm from the model's surface during stimulation by the tower anode/cathode apparatus for analysis of monopolar electrode surface sensitivity. (D) Specific geometry of the tip of the 5-cm-diameter monopolar electrode model.

electrode tips. Just below this transition, a strip 1.5 mm wide, and just above it a strip of 0.5 mm in width was used. The potentials recorded at the mid-strip width location along the surface and their area-potential products for these two additional special strips were summed with those of the other 2-mm strips. The values of each segmental strip can then be used to determine the manner in which the entire monopolar electrode records its potential by some type of weighted summation of the potentials. The presumed weighting functions can then be tested against the actual potential recorded by the monopolar needle electrode model.

Electrode Current Shunting Effects. The experimental apparatus described above was used with the stimulating ring 1 cm from the 5-cm monopolar model's tip. Measurements were recorded 1 mm from the surface beginning at the insulation edge and progressing distally in 1-cm increments until the conical transition at 6.5 cm. The 19° taper region was then measured at its midpoint and tip. These measurements were then repeated after the exposed metallic tip was covered by a thin insulating coating. Prior to coating the exposed region, the resistance of the monopolar model was measured directly from shaft to tip, and again, once placed in the normal saline, to a 3-cm stainless steel disk located 23 cm away at the tank's periphery. Following application of the nonconductive coating, the impedance was measured throughout by means of a normal saline soaked cotton ball to ensure a uniformly high impedance.

Monopolar Spatial Response. An apparatus was conducted with the capability of positioning the above constant current cathode/anode electrode pair along the surface and at various radial distances from the model's central axis. The cathode and circular anode were aligned to follow the conical tip's angle oriented perpendicularly to the modeled monopolar needle tip's angled surface, and could be incrementally positioned parallel to the surface (Fig. 1A and B). This constant current anode/cathode source could also be positioned at various radii extending from the model electrode into the volume conductor until the recorded response disappeared into the level of the experimental noise. Graphs were produced of amplitude measurements made every 4 mm along the surface, and into the volume conductor, as well as 2 mm on either side of the tip, and at 2 mm from the surface (Microsoft Excel 4.0, © 1985–1992 Microsoft Corporation). This was performed for the three monopolar models. Due to symmetry, the plotted planar response along one edge and radially away from the monopolar electrode model was translated to a three-dimensional weighting function to reveal the model monopolar's recording sensitivity.

Table 1. Comparison of Uniform Weighted Averaged versus Whole Model Amplitudes.*

Tip to source distance	Uniformly averaged surface values (μV)	Monopolar recorded potential (μV)
1 cm	118	129
2 cm	101	99
3 cm	81	85
4 cm	67	75

**Analysis of monopolar electrode surface sensitivity values recorded with the 5-cm-diameter monopolar needle model compared to calculated uniform surface area averaging of the measured responses from 1 mm radially away into the volume conductor at various stimulation source distances from the monopolar needle's tip.*

RESULTS

Monopolar Electrode Surface Sensitivity. The results for a simple average of potentials recorded 1 mm away from each strip of surface area from the 5-cm-diameter monopolar model over the entire exposed metal surface reveal a close approximation to that actually recorded for the needle as a whole (Table 1). The potential distribution recorded along and 1 mm from the model's surface are shown in Figure 2. If the monopolar tip recorded potentials preferentially, then values closer to those at the tip should be recorded by the monopolar model. Instead, a uniform area weighting function accurately predicted the monopolar's response (Table 1). These values

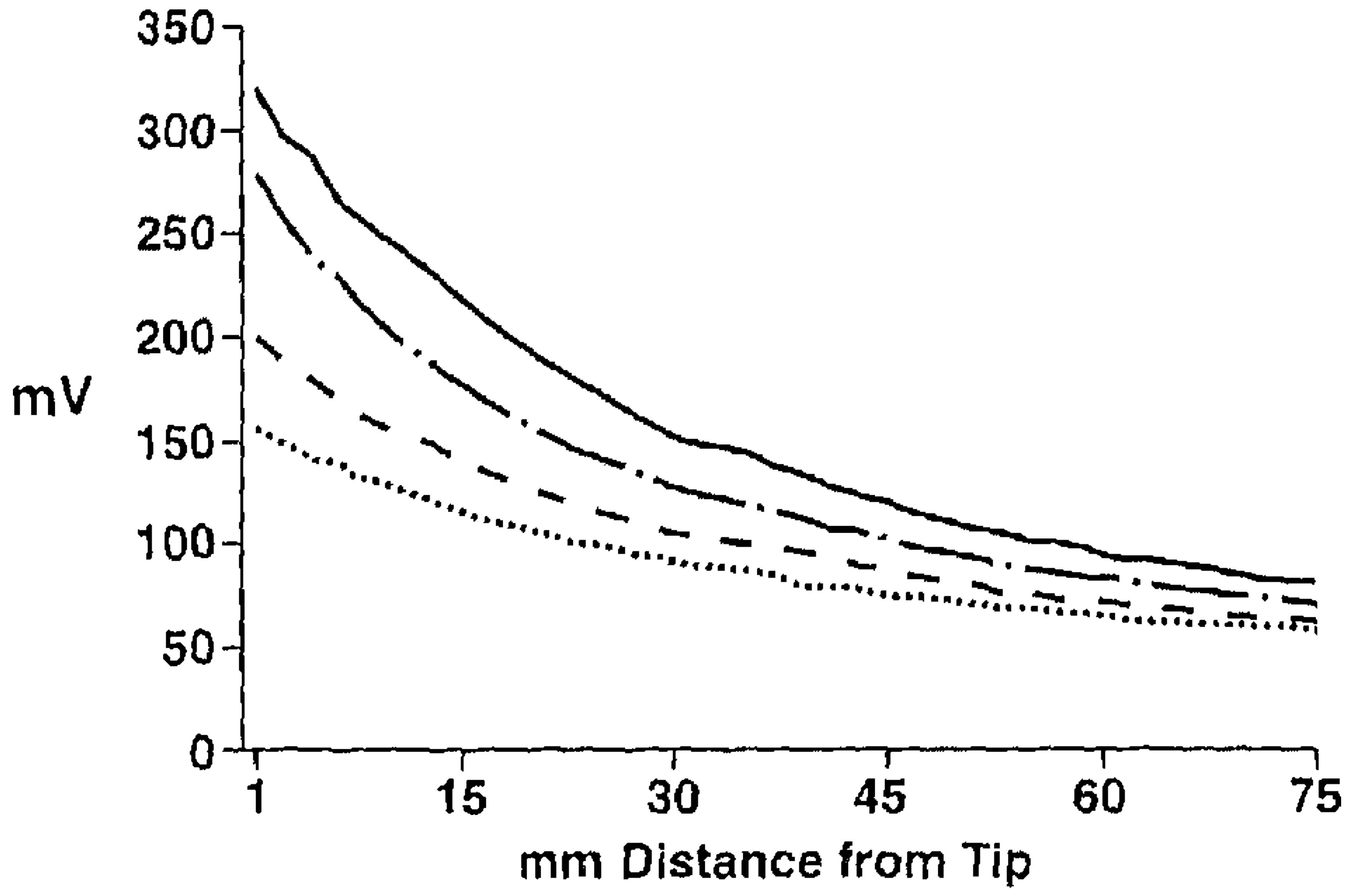


FIGURE 2. Potential amplitudes 1 mm from the model's edge over the length of the exposed conical metal surface recorded in response to a stimulator positioned coaxially below the monopolar model's tip at 1 cm (solid line), 2 cm (dashed–dotted), 3 cm (dashed), and 4 cm (dotted). See Figure 1A and C for experimental configuration.

are closer to those recorded near the midportion of the exposed metallic surface than near the tip. Any attempt to give preferential weighting to values recorded closer to the tip results in substantially greater error from that actually recorded by the monopolar model as compared to a uniform weighting function.

One source of experimental error is the electrical noise effects of the platinum iridium electrode, measured to be 4 μV, which should randomly combine to yield approximately 0.6 μV error to the calculated average (i.e., $0.6\ \mu V = 4\ \mu V/\sqrt{40}$ measures along the edge). However, the system noise measured with no stimulating current for the monopolar needle model was 12 μV. Another source of error was the measurement of the 2-mm strips, each of ±0.25 mm (nonaccumulative since an external marked reference was used), and the preciseness with which symmetry was obtained in aligning to the central axis of the volume conductor at ±0.25 mm. The central axis alignment distance variance did not appear to make measurable differences to our recorded potentials over an even greater range of several millimeters. Still another source of error is the uncertainty of 1 mm from the surface being the best distance to reflect the actual influence of the surrounding volume conductor to that strip of surface area. This was as close as we could practically come with any degree of accuracy in maintaining the radial distance uniformly (±0.1 mm). Given these variables, the simple uniform averaging results are equal to those actually recorded by the monopolar needle model within 10%, which is within our experimental error.

Electrode Current Shunting Effects. The impedance measured directly from the proximal shaft of the 5-cm monopolar model to its tip was found to be less than 0.2 Ω. The monopolar model's resistance to a 3-cm stainless steel flat disk located 23 cm away in the normal saline volume conductor was 200 Ω. The impedance of the thin insulation coating was greater than 5 $M\Omega/cm^2$ throughout the area of the formerly bare exposed metal. The measurements along the side of the 5-cm monopolar model in the normal saline volume conductor when coated with the thin insulating coating were compared to those recorded previously with the bare exposed metal. These comparison measurements were found to be within an average error of 5% without any significant trends from proximal to distal sites.

Monopolar Spatial Response. The distribution of values recorded by the 5-cm-diameter monopolar model over the hemiplane of a spatially distributed relative point source is shown in Figure 3A and B. One axis of this hemiplane is perpendicular to and radially away from the monopolar model's central axis. The other axis is parallel to the conical exposed metal's edge which makes an angle of 7.5° with its central axis (resulting in a tip angle for most of its surface of 15°). This axis remained at 7.5° despite the increased taper at the very tip (Fig. 1). From Figure 3B one can appreciate the more boldly indicated 10% of maximal amplitude (recorded at 2 mm away from the surface) isopotential, which lies closer to the tip than from the sides of the monopolar model. Using the scaling factor of 1 cm to 100 μm, this isopotential is approximately 420 μm from the side and 160 μm from the tip.

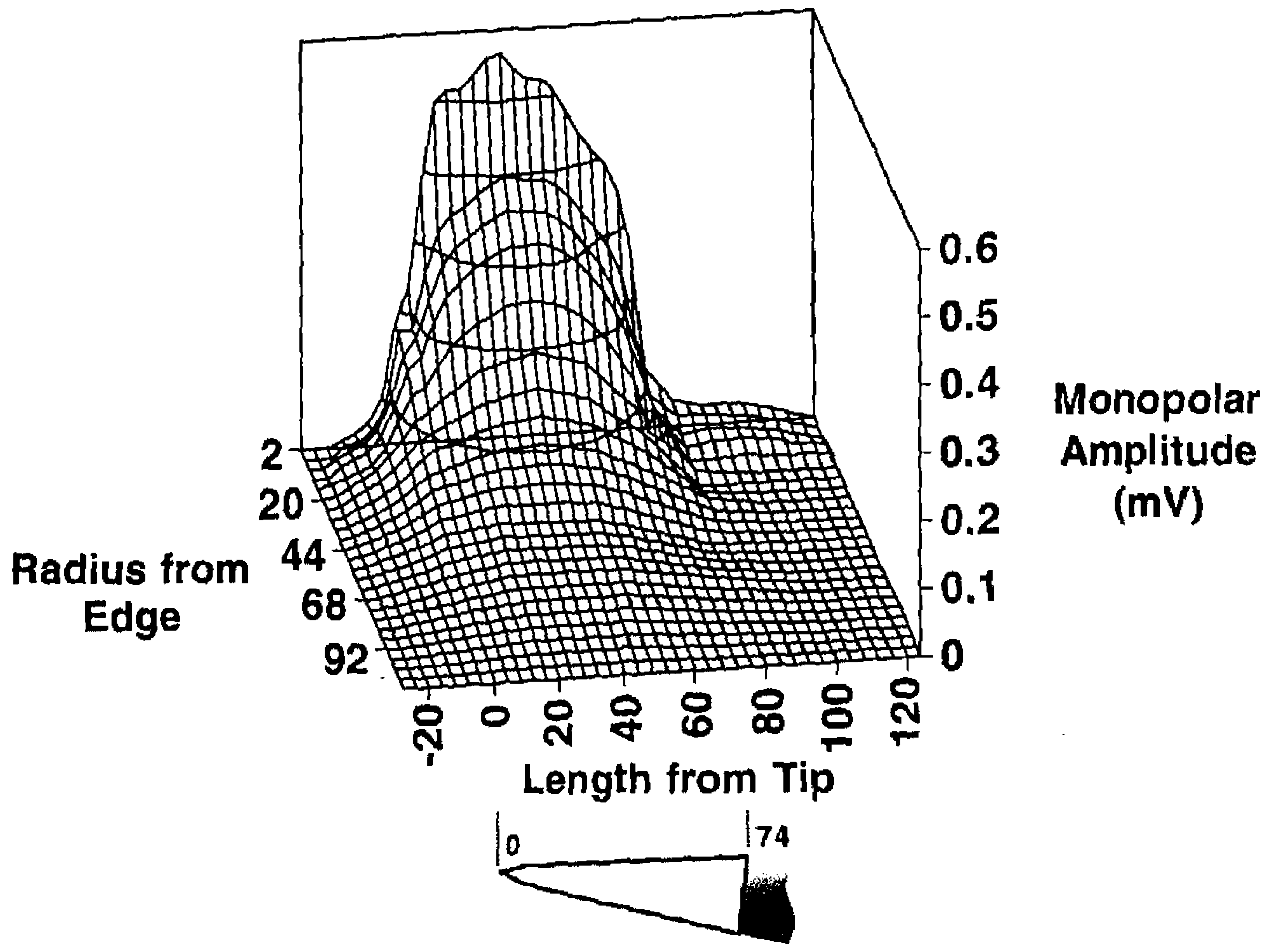
The smaller electrode models revealed very similar recorded potential distributions but with larger potentials recorded at similar sites. This effect, however, could not be extrapolated to the dimensions of a DMF monopolar needle electrode. The monopolar response depends in part upon the potential field distributions of our relative point source. In the case of the DMF electrode our relative point source becomes quite large, and no longer approximates a point source. The relative responses recorded by the three monopolar models at similar locations are shown in Fig. 4A–C.

DISCUSSION

A thin interface layer is formed between the metal of the electrode and the ionic conducting solution due to electrochemical reactions resulting in the so-called electrical double layer.[4,5,6,12] The potential recorded at all points of the monopolar model's metal is isopotential since the metal is a far superior conductor than either the double layer or volume conducting solution. This was demonstrated by the 5-cm-diameter monopolar model's resistance being directly measured to be less than 0.2 Ω as compared to 200 Ω in the saline solution when measured to a 3-cm stainless steel disk located 23 cm away. The contributing resistance of the normal saline can only be roughly approximately due to the complex geometry. For simplicity, its value should be less than that of a 6-cm-diameter cylinder of normal saline 23 cm long. With a normal saline resistivity of 20 Ω-cm, the resistance of such a cylinder of normal saline would be $[(20\ \Omega\text{-cm}) \times 23\ \text{cm}]/(\pi \times 3^2)$, or less than 17 Ω. Therefore, most of the measured resistance of the monopolar model in the volume conductor is from the electrical double layer's higher impedance.

A typical monopolar needle electrode would have an even greater relative impedance at this double layer

A. Monopolar Response to Various Stimulation Locations



B. Response Isopotentials from 0.010 to 0.570 mV

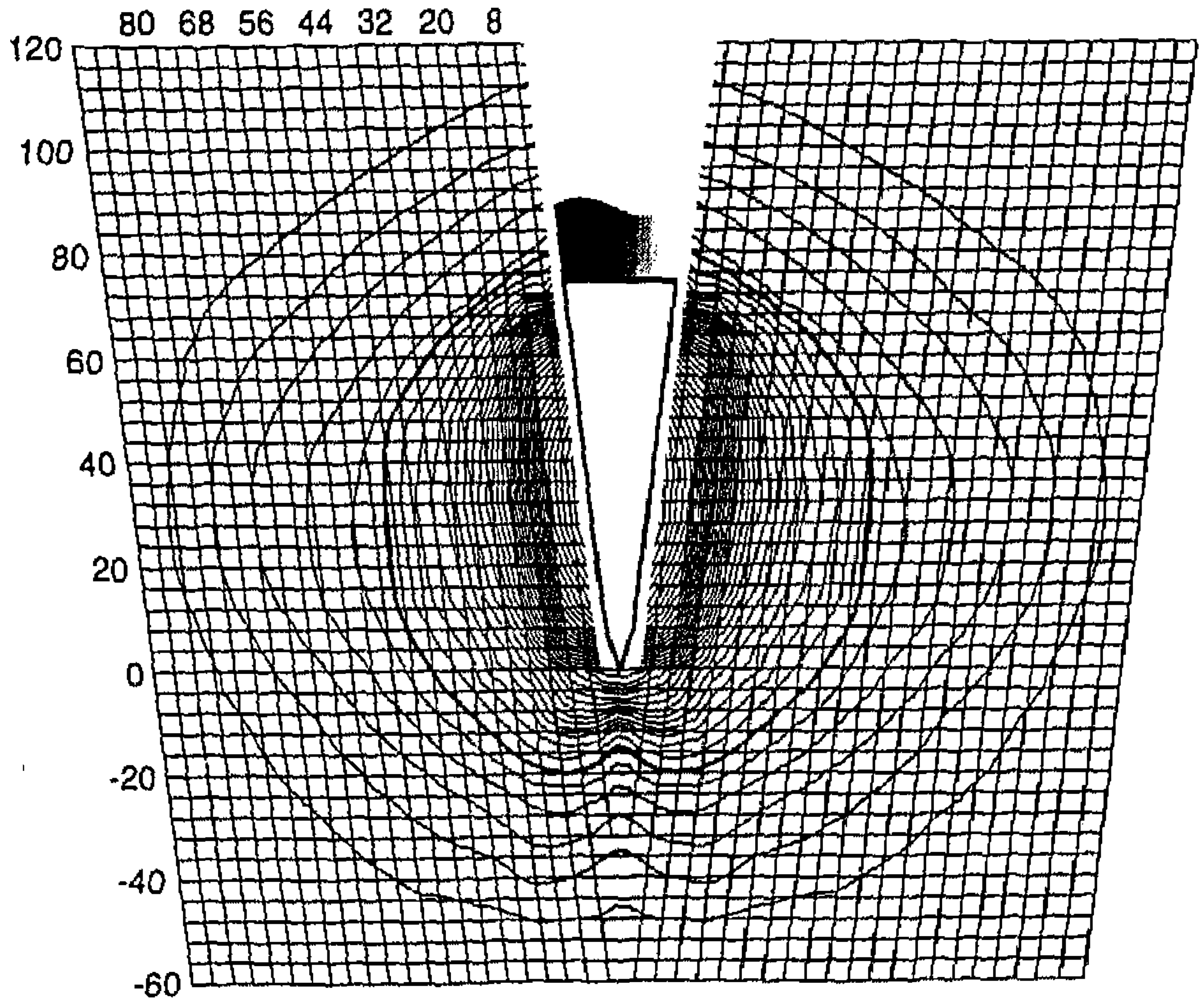


FIGURE 3. (A) The three-dimensional distribution as shown by a hemiplane with one axis (in millimeters) parallel to the edge and one perpendicular (in millimeters) to the central monopolar axis (with monopolar needle drawn to scale on figure, although its position would actually be behind the graph; its edge is equal to a "radius from edge" of 0 mm). (B) Isopotential lines are shown in 0.010-mV increments starting at 0.010 mV. The maximum potential is 0.57 mV measured for the cathode anode apparatus near the center of the exposed metal at 2 mm from the surface. Thus the bold isopotential, the sixth isopotential line in (equal to 0.060 mV), would be the approximate 90% decrement isopotential. Note this line is reached at 1.6 cm in front of the tip versus approximately 4.2 cm from the side due to a more rapid drop in sensitivity longitudinally beyond the tip than laterally out from the edge. This results in an "apple" shape of this isopotential. Physical dimensions are radial distance from edge (perpendicular to the central monopolar axis) and distance from the tip along an axis parallel to the edge, both shown in millimeters. By the scaling of 100 μm to 1 cm for this 5-cm-diameter monopolar model, the 90% isopotential above would translate to 160 μm in front and 420 μm lateral to the sides of an actual scale monopolar needle electrode.

due to its small surface area. Indeed, values commonly measured at these low frequencies are approximately 15–20 kΩ.[2] Relative to the impedance of this electrical double layer, the actual metal of the electrode appears as essentially 0 Ω.[5] Even less shunting effects would be anticipated for a typical clinically used monopolar electrode. The single isopotential that occurs on the metallic portion of the electrode is formed by some

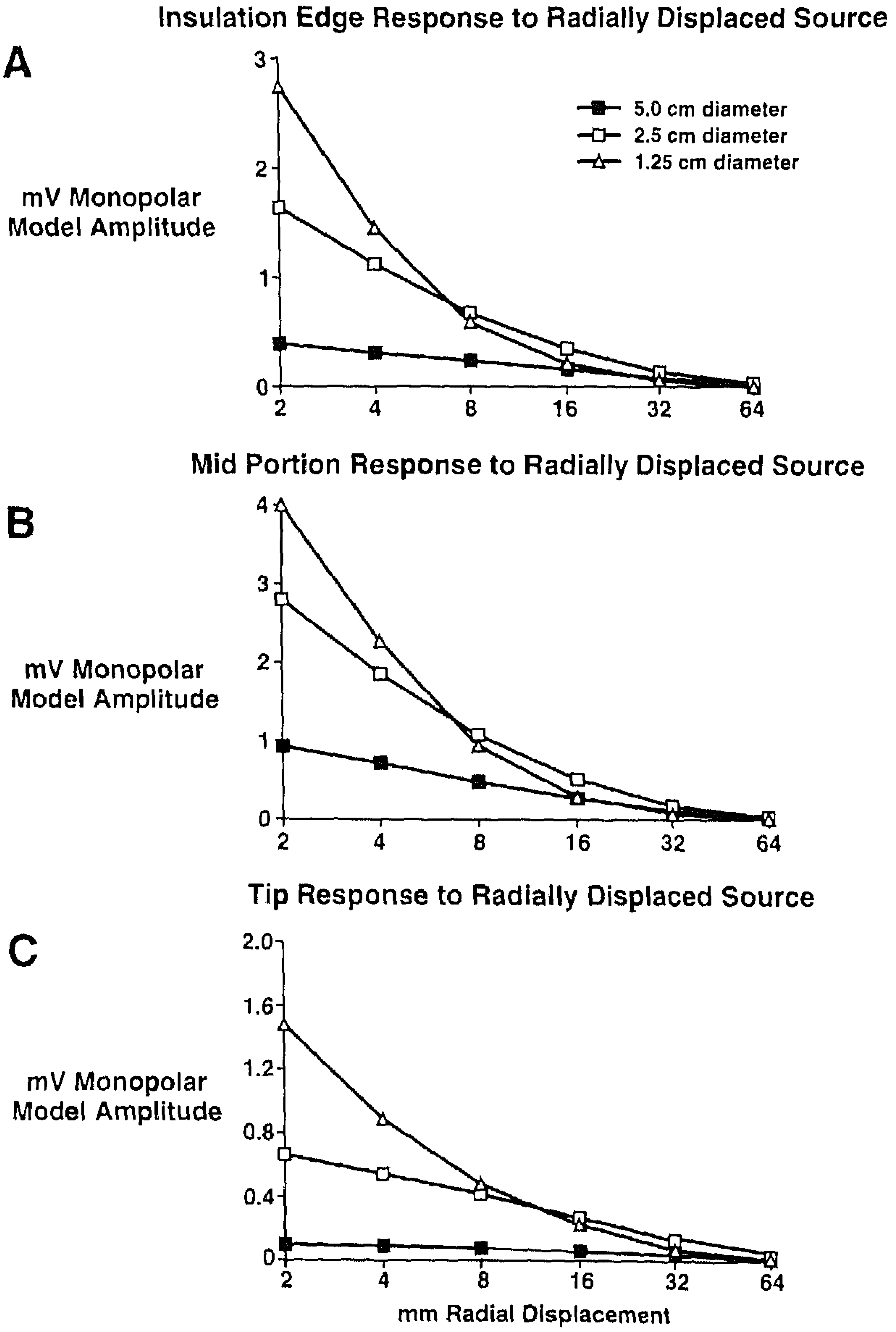


FIGURE 4. **(A)** Response amplitudes versus radial displacement from the insulation/exposed metal interface of the 5-cm-, 2.5-cm-, and 1.25-cm-diameter monopolar needle electrodes. Note that the 1.25-cm response curve declines more rapidly with radial distance than the larger two models, as expected due to its relative distance scaling (5 cm: 1 cm/100 μm; 2.5 cm: 1 cm/200 μm; 1.25 cm: 1 cm/400 μm). **(B)** Responses radial to mid portion of the conical exposed metallic surface for the three monopolar models. **(C)** Responses radial to the tip for the three monopolar models.

form of averaging of the potentials that occur in the volume conductor as seen across the relatively high impedance electrical double layer.

Due to this high impedance double layer effect, the electrode appears as a relative nonconductor placed within the relatively good conducting volume solution.[12] Our electrode models are much larger than standard monopolar needle electrodes. Since these enlarged models have significantly more surface area, their resistances should be much smaller than standard monopolar needle electrodes. If small enough, then one might expect some current shunting through the electrode which could distort the measured potentials in the volume conductor due to this current shunting effect. This was investigated during the analysis of electrode current shunting effects by purposefully placing a high impedance coating over the previously exposed metallic tip. Since no significant differences occurred in the potentials along the edge at 1 mm into the volume conductor, it can be deduced that even for our very large models there is sufficiently high impedance, due to the double layer, relative to the volume conductor's impedance that the monopolar electrode model appears to behave as a nonconductor to the current flow lines around it. This would be even more the case with an actual monopolar needle electrode which due to its smaller dimensions would have an even greater bilayer impedance. Its physical presence alters current paths, but not its electrical conductivity.

It seems very nonintuitive that placing an excellent metal conductor in a volume conducting solution results in it becoming a relative nonconductor due to this electrical double layer effect. However, this becomes more appealing when one considers that an electroencephalographic subcutaneous electrode with a measured impedance of 5 kΩ or more in the body has less than 1 Ω of purely metallic electrical impedance when measured outside the body with an ohmmeter. Thus, the impedance of electrodes placed in volume conductors is largely determined by the impedance of the electrical bilayer which is much greater than that of the metal of the electrode or the impedance of the surrounding volume conductor solution.

The electrode's metal is isopotential; this is presumably influenced to some degree by all potentials in the nearby volume conductor acting across this interface, which in some fashion summate to the overall monopolar potential recorded. One might conjecture that each portion of the volume conductor would have equal weight in determining the potential sensed by the electrode. Indeed, the values obtained by calculating a uniform weighting of the entire surface area's potentials just outside the electrical double layer predicted the monopolar model's potential within our experimental error (Table 1).

If the tip were preferentially weighted,[8] values closer to those of the tip should have been obtained from the model as a whole as opposed to that obtained from a uniform area weighting. Values 1 mm into the volume conductor near the tip (Fig. 2) were typically 3–5 times the magnitude those near the mid portion of the exposed metal, or near the insulation border. Yet, the monopolar model values were closer to those measurements 1 mm into the volume conductor near the mid or proximal portions than to those near the tip. The midportion 2-mm strips had larger surface areas and a lower spatial gradient than near the tip. However, even when the cathode/anode stimulating tower was 4 cm from the tip, the lower spatial gradient midportion measurements appeared to "weigh" more than the tip in a fashion that was predictable by the amount of surface area alone. Indeed, the largest surface area is in the 2-mm strips near the insulation border and these regions had potentials only slightly below that of the monopolar model's response. These large area strips effectively "averaged down" the significantly larger potentials which occurred in the volume conductor near the tip.

Monopolar model recording from the constant dipolar point source stimulation also showed little evidence of higher values recorded when the stimulating source was near the tip than when along more proximal locations. Indeed, the middle third of the electrode has a relatively broad flattened peak near the middle of the exposed metal surface as opposed to any peak near the tip. One would expect a larger potential when this constant dipolar source is near the tip if indeed preferential recording occurs at this site. This type of preferential recording was not observed. The uniform weighting by surface area helps one understand why small movements of the monopolar electrode in muscle tissue are tolerated without substantial decrement in the recorded potential, which is a commonly appreciated clinical experience. A transverse and relatively small diameter muscle fiber can maintain a similar amount of surface area contact with the larger monopolar needle electrode tip despite movements of comparable size to the exposed tip.

Given this form of uniform averaging one can consider whether a monopolar needle could record an intracellular potential with the typical amplitudes seen in electrophysiological studies by only a small portion of its surface area being exposed to the intracellular volume through a possible membrane rent or tear.[3] A 20 μm by 20 μm window into the side of a muscle fiber, or 400 μm^2 which equals 0.0004 mm^2 area exposed to the muscle fiber's interior, would compare to 0.24-mm^2 typical monopolar needle electrode surface area. One would then predict that the intracellular component contributing to whatever other potentials the monopolar electrode is detecting would be averaged in as 0.0004/0.24 or 0.0017 times the amplitudes of the internal action potential. Thus a -80 to 30-mV internal action potential would be surmised to be recorded as a -136 to 51-μV, or 187-μV peak to peak potential by the monopolar needle electrode, which is within the physiologically recorded values observed. A smaller window would result in smaller recorded amplitudes. From a purely amplitude perspective, such an intracellular recording appears plausible, though this study does not purport to provide any evidence that such recordings are possible.

Considering this uniform averaging, one can speculate regarding the changes that might be expected for various monopolar electrode conditions. A sharper or shallower tapered monopolar electrode would not preferentially affect tip recording because the ratio of areas at the tip of those more proximal remains the same. A sharper taper results in less surface area at the tip, but by percentage the same reduction in area for strips more proximal as well. A similar result occurs for more shallow tapered electrodes, resulting in no net ratio difference. Blunting or rounding of the tip, however, would result in greater relative contribution of the potentials recorded near the tip, though the mid and proximal shaft of exposed metal would still have the greatest influence on overall averaging of potentials recorded. Peeling back the insulation to expose more surface area would result in more dilution of potentials recorded near the tip or near any one small portion of the electrode. One would expect a drop in the overall recorded amplitude of such a potential and this is consistent with the findings of Chu et al.[1]

A trend for a larger voltage amplitude to be recorded as the electrode model size is diminished is shown (Fig. 4). This is consistent with the fact that much smaller currents from a typical 50-μm-diameter muscle fiber are recordable at measurable voltage amplitudes with a routine monopolar needle electrode. The radial decline in amplitude response per distance also occurs more quickly for the smaller electrodes, in keeping with the known much smaller spatial recording extent for standard clinically used monopolar electrodes as compared to the spatial extents measured for our much larger models.

The physical presence of the electrode has been computer modeled to enhance or enlarge the potentials recorded compared to those which would theoretically occur in that location if the recording electrode had no physical dimensions.[12] This is due to a type of wall boundary effect which concentrates the currents as they must pass around the physical dimensions of the electrode. The recorded potential of our monopolar model is found to drop more precipitously longitudinally away from the tip than it does radially away from the tapered shaft's exposed side (Fig. 3). This is perhaps due to this enhancing boundary effect which elevates the potentials seen near the edge.[10] Beyond the tip no such wall exists and the potentials decline with greater rapidity per unit distance. This field distribution of responses suggest that sources will contribute more significantly, and over greater distances, when radially displaced, than when longitudinally displaced from the monopolar recording surface. This wall boundary effect may also account for the relatively similar recording sensitivity volume of a concentric needle electrode despite its smaller active recording surface. The flat bevel itself may tend to magnify potentials in front of it to a greater degree than the convex surface of a monopolar electorde. The simulation of Nandedkar et al.[9] suggests that less than 10% amplitude is added by potentials more than 600 μm in front of the active recording surface. This compares to the scaled 420 μm distance at which our 10% isopotential is found radially from the monopolar model's edge. This results in similar recording volumes for the hemispheric territory of the concentric compared to our recorded monopolar volume (approximately 0.45 μm^2 each). This may account in part for the similar recorded motor unit action potential durations whether a monopolar or concentric needle electrode is used.

The actual sensitivity pattern is more of an apple shape (Fig. 3B) centered at the middle of the exposed tip, than the previously assumed spherical pattern centered at the tip. The greatest recording strength appears to be along the greater exposed surface areas where the decrement with distance is much smaller than the precipitous decline near the insulation or the tip. Thus the peak sensitivity is approximately mid exposed shaft, not at the tip. The spatial response declines rapidly beyond the tip or proximal to the insulation edge. This results in a tuck at the tip and proximal insulation edge versus the more spherical pattern around the mid exposed shaft, resulting in an apple shape distribution centered at the mid exposed shaft.

Appreciation of what portions of the volume conductor are selectively recorded and to what extent is important to interpreting basic and quantified electrophysiologic data. Interpretation of data back to the fiber level requires this knowledge. Relating quantitative electromyographic results to normal and pathophysiological processes also demands an understanding of what portion and geometry of the muscle fibers are preferentially recorded.[1] Since sensitivity drops off more quickly along the direction of the shaft than radially away, one would expect optimizing motor unit action potentials to occur more rapidly over shorter distances with longitudinal repositioning than radial, and to remain somewhat stable over the length of the exposed metallic tip. Radial repositioning (which generally requires withdrawing and reinserting the needle electrode) will result in less rapid changes per distance. Radial pressure to the needle electrode during insertion (and thereby small movements intramuscularly) should be relatively stable with only small changes occurring as a result of such pressures. These expectations seem consistent with clinical practice. Another intriguing consideration is the number of muscle fibers sampled within the 90% attenuation area (Fig. 3B). By considering the geometry, and ignoring the substantial effects of the needle electrode in displacing fibers, one would expect slightly more fibers to be sampled per insertion if the electrode is inserted relatively parallel to the fiber direction than if in the more customary perpendicular orientation to the muscle fibers.

Our study looks at the first approximation of the monopolar electrode's intramuscular spatial sensitivity, which is the response in a uniform volume conductor. This study examines the low-frequency response characteristics of a monopolar needle electrode model in a uniform volume conductor. This is the first study of which we are aware that quantifies, by physical model, the quasistatic spatial recording characteristics of a monopolar electrode.

This study provides a physical model that demonstrates a uniform weighting factor over the exposed surface of a monopolar electrode model in an isotropic volume conductor. The spatial recording characteristics are demonstrated and found to be significantly different than the commonly assumed spherical recording territory centered at the tip. A more apple shape of recording sensitivity (Fig. 3B) is found which is centered over the midportion of the exposed conical tip. This investigation will hopefully serve to catalyze additional computer modeling and clinical research of the complex spatial recording characteristics of the monopolar needle electrode so that more varied and inhomogeneous conditions, such as actual muscle, can be modeled and substantiated.

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