Computer-based Finite Element Modeling of Insulated Tuohy Needles Used in Regional Anesthesia

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Background: Differences in needle design may impact nerve localization. This study evaluates the electrical properties of two insulated Tuohy needles using computational finite element modeling.

Methods: Three-dimensional geometric computer-based models were created representing two 18-gauge, insulated Tuohy needles: (1) with an exposed metal tip and (2) with an insulated tip. The models were projected in simulated human tissue. Using finite element methodology, distributions of current-density were calculated. Voltages in the modeled medium were calculated, and activation patterns of a model nerve fiber around the tip of each needle were estimated using the activation function.

Results: Maximum current density on the exposed-tip needle occurred along the edge of the distal tip; the distal edge was 1.7 times larger than the side edges and 3.5 times larger than the proximal edge. Conversely, maximum current density occurred along the proximal edge of the insulated-tip Tuohy opening; the proximal edge was 1.9 times larger than the side edges of the opening and 3.5 times larger than the distal edge of the opening. Voltages generated by the exposed-tip needle were larger and had a wider spatial distribution than that of the insulated-tip needle, which restricted to the area immediately adjacent to the opening. Different changes in threshold were predicted to excite a nerve fiber as the needles were rotated or advanced toward the modeled nerve.

Conclusions: The needles displayed different asymmetric distributions of current density and positional effects on threshold. If this analysis is validated clinically, it may prove useful in testing stimulating needles before clinical application.

The use of insulated needles and peripheral nerve stimulation has been adopted to enhance the accuracy of local anesthetic delivery and improve the success of regional anesthesia. To achieve this aim, a variety of needle designs in clinical practice have different lengths, diameters, lumens, bevel tips, and degrees of insulation. They are often marketed for the same application but are purported to have unique advantages. Yet, manufacturers are not required to supply data about a needle’s performance, and rarely are there analyses of the electrical characteristics of individual products or comparisons between designs. The purpose of the current study was to characterize the electrical properties of two Tuohy-tipped needles used in regional anesthesia.

In clinical practice, anesthesiologists often detect subtle differences from repeated use and personal experience or the experience of others. Nuances such as needle insertion angle and bevel rotation can change the evoked response as well as alter the necessary current to stimulate. Needles with a Tuohy tip design seem particularly prone to these variations. One possible explanation may be differences in the directional spread of current from the needles created by the lack of symmetry and the degree of exposed metal on the needle tip. This hypothesis is supported by previous investigations of the effects of electrode geometry on patterns of current flow and neural stimulation.1–3 These computer modeling studies demonstrated that the distribution of current density on the electrode surfaces, the patterns of current flow in the tissue, and the threshold for and patterns of neural stimulation were strongly influenced by the size and shape of the electrode. Therefore, it seems possible that the clinical differences observed between needles may be related to their design and that these differences could be predicted by quantitative analysis.

The primary goal of the study was to use computer-based finite element models to predict the spatial distribution of the current density surrounding two similar insulated Tuohy needles used for continuous catheter insertion. The second objective was to estimate how changes in position and orientation relative to a modeled nerve fiber affected activation thresholds.

Materials and Methods

Two different models were implemented to represent two commercially available Tuohy needles with different designs (figs. 1 and 2). The exposed-tip model is a partially insulated 18-gauge Tuohy-tip needle for continuous peripheral nerve block with an exposed metal tip (StimuCath; Arrow, Reading, PA). The insulated-tip model is an insulated metal 18-gauge Tuohy-tip needle for continuous peripheral nerve block with an insulated tip (Contiplex Tuohy; B. Braun, Bethlehem, PA).

Finite Element Model of Stimulating Needles

First, a micrograph of each needle was made, and the geometry of each needle was measured (figs. 1A and 2A). For purposes of model comparison and because of the close similarities in the needle dimensions, the OD (1.36

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mm), insulation thickness (40 μm), and metal thickness (240 μm) for each needle were approximated to be the same. These measurements were then used to create three-dimensional computer models of each stimulating needle (figs. 1B and 2B) using COMSOL Multiphysics version 3.2 (COMSOL Inc, Burlington, MA). Models were implemented in the three-dimensional, electromagnetics, conductive media DC module of the software.

The current density on the surface of the needles and electrical voltages in the modeled tissue were calculated using the finite element method. Finite element analysis is a numerical method to solve partial differential equations (in this case, Laplace’s equation) over a complex domain (such as a needle with variable geometry). The domain, including the needle, and the surrounding box, meant to represent the surrounding tissue, were discretized into a mesh of tetrahedral elements, as required by the finite element method. The density of the mesh, or equivalently, the size of the elements was variable throughout the domain. Smaller elements (finer discretization) were defined for regions near the needle (greater than 10 times more elements per cubic mm) than for regions further from the needle in the surrounding modeled tissue.

The goal of varying the mesh size was to enhance precision in the area of interest (needle surface) without introducing additional computational burden associated with using small elements throughout the domain. The resulting models had 132,655 and 84,500 tetrahedral elements for the exposed- and insulated-tip needles, respectively. The difference in the number of elements in the two models was a direct result of the differences in the needle geometries. The larger metal surface area of the exposed-tip needle necessitated a larger volume of finer discretization (approximately 57,000 elements) than the smaller “lumen” exposure of the insulated tip needle (approximately 5,600 elements).

The box representing the tissue surrounding the needle was 10 × 10 × 15 mm. This was based on the premise that, under clinical conditions, motor responses occur when the needle is less than 10 mm from the nerve. The outer boundary was set to 0 volts (ground), and the needle metal was set to 5 volts. The metal of each needle was modeled with a constant voltage condition to represent the nonuniform current density across the metal surface. This mimics the in vivo situation; because the needle metal is a good
conductor, it will have the same voltage throughout the metal, but the distribution of current density on the surface will be nonuniform. The electrical conductivities (S/m = siemens/meter) of each element varied across the domains of the model. The modeled tissue was assumed to be electrically homogeneous, and a value of 0.2 S/m representative of muscle tissue was chosen. A high resistivity of 10E-10 S/m was used for the needle insulation, and a low resistivity of 10E8 S/m was used for the needle metal. Because needles in clinical practice are usually flushed with an ionic solution (local anesthetic) before insertion, saline (1 S/m) was used to model the space within each needle shaft and opening.

The output of the model was the three-dimensional distribution of current density and voltages in the modeled region. The total current passing into the modeled tissue from the needle was calculated by integration of the current density of the elements along the needle surface. For presentation purposes, three separate images were produced representing the voltages in the x-z and y-z planes as well as the current density along the surface of the Tuohy opening. Quantitative comparisons of maximum and minimum values were also made for descriptive purposes.

**Calculation of Nerve Fiber Activation Patterns**

Calculations of the activating function were used to determine if variations in the voltages generated in the model tissue around each needle would activate (stimulate) a nerve fiber (axon) differently. For demonstration and simplification purposes, a single nerve fiber was used as a modeling substitute for a complex motor nerve, which would contain thousands of fibers.

Prediction on the activation of a nerve fiber by extracellular voltages can be made using the “activating function.” Nerve fiber activation occurs when the transmembrane voltage (the difference between the intracellular and extracellular voltages) exceeds the threshold to generate a propagating action potential. The propensity of extracellular voltages to generate an action potential can be estimated by calculating the second spatial difference of the extracellular voltages present along the nerve fiber – a quantity known as the activating function, $f_0\Delta^2 V_e/\Delta x^2$. In this model, distributions of $\Delta^2 V_e/\Delta x^2$ for a nerve fiber oriented perpendicular to the needle were

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**Fig. 2. Distribution of current density on the insulated-tip Tuohy needle.** (A) Photomicrograph of the needle tip. (B) Geometry of finite element model of the needle tip. (C) Current density distribution perpendicular to the plane of the needle orifice. (D) Current density perpendicular to the needle orifice (log scale) along a line parallel to the long axis of the needle and bisecting the orifice. (E) Current density perpendicular to the needle orifice (log scale) along a line perpendicular to the long axis of the needle and bisecting the orifice.
calculated in the modeled tissue medium from the voltages solved by the finite element models, with 2 mm used as the space step, $\Delta x$ (i.e., the internodal spacing for a 20-μm-diameter nerve fiber). The peak value of the activating function was determined at different radial positions and at different distances from the tip of the needle ($r = 1, 2, \text{ and } 4 \text{ mm}$) to the modeled nerve fiber. The purpose was to simulate the changes in nerve activation that might occur in clinical practice as the Tuohy needles were rotated or advanced closer to the nerve. The relative difference in excitability, quantified as the differences between the peak values of the activating function ($f_{\text{max}} - f_{\text{min}}$/$f_{\text{max}} + f_{\text{min}}$), were compared between pairs of nerve fibers in four different radial positions, representing 360-degree rotation of the needle about its shaft at the three different radii from the needle tip.

**Results**

There were substantial differences between the exposed-tip needle and the insulated-tip needle that impact their use for nerve proximity detection.

**Distribution of Current Density**

The different patterns of insulation on the needle tips led to differences in the distribution of current density on the two needles. The current density distributions on each needle (i.e., perpendicular to the distal opening of the needle) are shown in figures 1C and 2C, and the current density along the needle orifice parallel and perpendicular to the needle shaft are show in figures 1D and 2D and figures 1E and 2E, respectively.

**Exposed-tip Needle.** When analyzing the oval-shaped needle opening, the maximum current density occurred on the distal end of the opening (nearest the needle tip) (fig. 1C). This magnitude was 1.7 times larger than the current density on the side edges of the needle opening and 3.5 times larger than the current density on the proximal edge of the needle opening. Furthermore, when comparing the entire opening, the current density along the outer edge of the metal was higher than the current density along the inner edge of the metal, and this was consistent around the entire circumference.

**Insulated-tip Needle.** In contrast, the maximum current density occurred on the proximal end of the opening of the needle tip (closer to the shaft than the tip) (fig. 2C). This magnitude was 1.9 times larger than the current density on the side edges of the orifice and 3.5 times larger than the current density on the distal edge of the needle opening.

In addition, current flowed from the modeled conductive solution (saline) that filled the lumen of each needle. With the exposed-tip needle, the current density was lowest within the lumen of the needle and high along the exposed metal. In contrast with the insulated-tip, the current density was highest in the lumen and zero along the unexposed, insulated portions of the needle.

**Voltages in the Modeled Tissue**

The voltage distributions in the modeled tissue region are presented in figure 3. The voltages generated by the exposed-tip needle were larger and spread over a broader region than the smaller voltages generated by the insulated-tip needle, which were restricted to the area immediately adjacent to the needle opening.

**Estimated Patterns of Nerve Fiber Activation**

Calculations of the activating function from the voltages in the modeled tissue to predict nerve fiber activation revealed different patterns of activation between the two needles (fig. 4). The exposed-tip needle produced the greatest activation (i.e., lowest thresholds) closest to the distal end of the opening (nearest...
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Fig. 4. Effect of rotating each needle about its long axis on the relative threshold for activation of a model nerve fiber lying at different positions (labeled 1–4) and radii (1, 2, or 4 mm) from the needle. (A) Geometry of finite element model of the needle inserted into the tissue and positions of model nerve fiber, which ran perpendicular to the plane of the page. (B) Relative differences in excitability as the exposed-tip needle was rotated 360 degrees, quantified as the differences between the peak values of the activating function \(|f_{max} - f_{min}|/|f_{max} + f_{min}|\) for the modeled nerve fiber in the four different radial positions at three different distances between the needle and the fiber (radius). (C) Relative differences in excitability as the insulated-tip needle was rotated 360 degrees.

the needle tip) and produced activation at similar distances from all areas of the exposed metal. In contrast, the insulated-tip needle produced the greatest activation closest to the proximal edge of the orifice and generated no activation distant from that focal point.

The exposed-tip and insulated-tip needles exhibited different patterns of activation as the needle was rotated about its long axis. The difference between the maximum (i.e., low threshold) and minimum (i.e., high threshold) activating function was quantified for a nerve fiber represented to be at a 1-, 2-, or 4-mm radius from the needle shaft (fig. 4). The changes in threshold with rotation were larger for the closer nerve fiber for both needle designs. However, for the more distant nerve fiber locations, the changes in threshold with rotation were substantially greater for the insulated-tip needle than the exposed-tip needle. Thus, the insulated-tip needle is expected to have a greater sensitivity of threshold to needle rotation during nerve localization than will the exposed-tip needle.

Discussion

The results of this study demonstrate that the electrical properties of two commonly used needles can be analyzed by applying computational finite element modeling. This analysis demonstrates that small changes in the patterns of insulation produce needles with substantially different distributions of current density. The distributions of current were asymmetric, as a result of their insulation patterns and the Tuohy geometry. This asymmetry gave rise to differences in the changes in nerve fiber activation that occurred as the needles were rotated about their long axes. Thus, needles designed for the same purpose and with “near equivalent” geometries exhibited unique electrical characteristics that could account for variations in clinical performance.

One aspect of clinical performance that was suggested from the voltage distributions in the modeled tissue and subsequent estimation of nerve fiber activation was the directionality of current flow and activation patterns around the Tuohy tips. Because of the geometry, insulation, and the fact that current was preferentially transmitted from metal edges, both needles were more likely to elicit activation in the area nearest the opening. Further, the insulated-tip needle exhibited a greater sensitivity to needle rotation than did the exposed-tip needle. Clinically, this would suggest that rotation could be used to help or should be considered when determining the location of a nerve in the z-direction in addition to the usual maneuvers of needle alignment.

The data also demonstrate that designing an ideal insulated needle for electrical nerve localization involves compromises that may provide advantages in one scenario and disadvantages in another. For example, the greater conductive surface of the exposed-tip needle provides a larger area for nerve fiber activation, which was greatest at the Tuohy opening but also present proximal and posterior to the opening as well as other areas around the tip. Clinically, this may produce a more sensitive needle that would provide feedback as the operator approaches a nerve. Conversely, a nerve may be activated unintentionally in areas distant from the orifice, therefore decreasing its specificity. In contrast, the insulated-tip has a very limited area of exposure that minimized the surrounding voltages and theoretically enhanced specificity. The shortcoming is that in a clinical situation there could be other areas besides the opening that could be in close or ideal proximity to a nerve and may not elicit a motor response.

One finding that was not intuitive from visual inspection or our previous clinical experience was the area of greatest current density and activation of the insulated-tip needle. Previously, we operated under the clinical assumption that the greatest electrical stimulation occurred at the very distal end of the needle tip. In fact, the data in this study demonstrate that the distal end of the...
needle tip has limited current density and produces limited activation. Therefore, in a clinical situation, depending on the needle orientation, it is possible that it may need to be advanced until the proximal edge of the opening is closest to the nerve.

To our knowledge, this is the first study using computational finite element modeling to analyze insulated Tuohy needles in regional anesthesia and to combine it with the activating function to estimate nerve fiber excitation. A previous study demonstrated the utility of the finite element methodology for this purpose, analyzing two differently sized needles for peripheral nerve localization. In that study, the different sizes were shown to generate different electrical fields that could account for differences in performance when a smaller needle is used as a nerve locator before inserting a larger caliber catheter introducer needle. More recently, Ercole demonstrated that this methodology was also useful for analyzing the electric field around uninsulated needles. In that study, he was able to demonstrate that the electric field was highly localized and extremely sensitive to small volumes of injectate.

An advantage of finite element analysis is the ability to input a specific geometric structure that is conducive for three-dimensional imaging and, in this case, allows the electrical footprint of the needle to be analyzed with the process of nerve activation. This contrasts with previous studies of needles used in regional anesthesia that created two-dimensional maps of voltage around the needle. Voltage distributions were sampled manually from a current stimulator attached to a needle either lying in a shallow saline bath or immersed in an electrophoretic gel. Although both of these approaches offer useful information, they lack the precision and flexibility of finite element modeling. Further, previous efforts using analytical solutions lack the flexibility of the methodology used in this study. Nevertheless, despite the valuable information gained in this study, several limitations in methodology exist. In particular, for purposes of analysis, the model used in this situation assumes that the needle and nerve are surrounded by a homogeneous medium, and therefore does not include the effects of conductive boundaries that may be created by tissue planes. These conditions can distort the distribution of current density and voltages and thereby influence the patterns of nerve stimulation. In addition, the surface area of each needle was assumed to be perfectly smooth, which is not the case in reality. Rough areas can increase geometric surface area and generate substantial changes in current density distribution. Also, as with other models of electrical stimulation, the nerve considered in this model consisted of a single fiber and did not factor in the complexity of a multifascicular nerve. Finally, the analysis in this study incorporates a single perpendicular needle and a limited number of nerve fiber positions and therefore requires extrapolation for the infinite number of potential relationships.

In conclusion, the results of this study demonstrate that two commonly used insulated Tuohy needles have different distributions of current density. The asymmetric patterns and areas of maximal current density may not be intuitive from visual inspection. By analyzing these needles with a mathematical model of activation, possible variations in clinical performance were predicted. This methodology may be helpful in assessing electrical characteristics of new needle designs prior to their introduction in clinical practice.

References