Current Threshold for Nerve Stimulation Depends on Electrical Impedance of the Tissue: A Study of Ultrasound-Guided Electrical Nerve Stimulation of the Median Nerve

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BACKGROUND: Understanding the mechanisms causing variation in current thresholds for electrical nerve stimulation may improve the safety and success rate of peripheral nerve blocks. Electrical impedance of the tissue surrounding a nerve may affect the response to nerve stimulation. In this volunteer study, we investigated the relationship between impedance and current threshold needed to obtain a neuromuscular response.

METHODS: Electrical nerve stimulation and impedance measurements were performed for the median nerve in the axilla and at the elbow in 29 volunteers. The needletip was positioned at a distance of 5, 2.5, and 0 mm from the nerve as judged by ultrasound. Impulse widths of 0.1 and 0.3 ms were used for nerve stimulation.

RESULTS: A significant inverse relationship between impedance and current threshold was found at the elbow, at nerve-to-needle distances of 5 and 2.5 mm ($P = 0.001$ and $P = 0.036$). Impedance values were significantly lower in the axilla (mean 21.1, SD 9.7 kohm) than at the elbow (mean 36.6, SD 13.4 kohm) ($P < 0.001$). Conversely, current thresholds for nerve stimulation were significantly higher in the axilla than at the elbow ($P < 0.001$, $P < 0.001$, $P = 0.024$). A mean ratio of 1.82 was found for the measurements of current thresholds with 0.1 versus 0.3 ms impulse duration.

CONCLUSIONS: Our results demonstrate an inverse relationship between impedance measurements and current thresholds and suggest that current settings used for nerve stimulation may require adjustment based on the tissue type. Further studies should be performed to investigate the clinical impact of our findings.

(Anesth Analg 2009;108:1338–43)

The current intensity needed to obtain a motor response when stimulating a nerve varies among individuals. It can also vary among different nerves in the same person.[1] Furthermore, motor responses to electric nerve stimulation cannot always be obtained despite an appropriate perineural needle position and current output.[2] Understanding the mechanisms causing a variation in current thresholds may improve the safety and success rate of nerve block procedures. The conductive properties of the tissue surrounding the nerve can be one of the factors affecting nerve stimulation.

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Accepted for publication October 6, 2008.

Supported by the Division of Anesthesiology and Intensive Care Medicine, Rikshospitalet University Hospital, Oslo, Norway.

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DOI: 10.1213/ane.0b013e3181957d84

Electrical impedance is a measure of the opposition to the flow of alternating current through a tissue. The unit for impedance measurements is ohm. The aim of the present study was to investigate the effect of tissue impedance on the current threshold required to obtain a motor response, when stimulating the median nerve in volunteers, using high-frequency ultrasound to determine the positions of the nerve and the stimulating needle.

METHODS

The protocol was approved by the regional ethical committee (Regional Komité for Medisinsk Forskningsetikk, Helseregion Sør, Oslo, Norway). Twenty-nine healthy adult volunteers were included in the study after giving informed written consent. With the volunteer in the supine position, the left arm was abducted to 90°. The nerves were examined using a Philips iU22 ultrasound unit (Philips Medical Systems, Bothell, WA) with a Philips L17–5 high-frequency linear 38-mm probe with a range from 5 to 17 MHz. The median nerve was initially visualized in its complete course in the arm. For nerve stimulation and measurements, the nerve was examined approximately 1.5 cm distal to the axillary fold (proximal

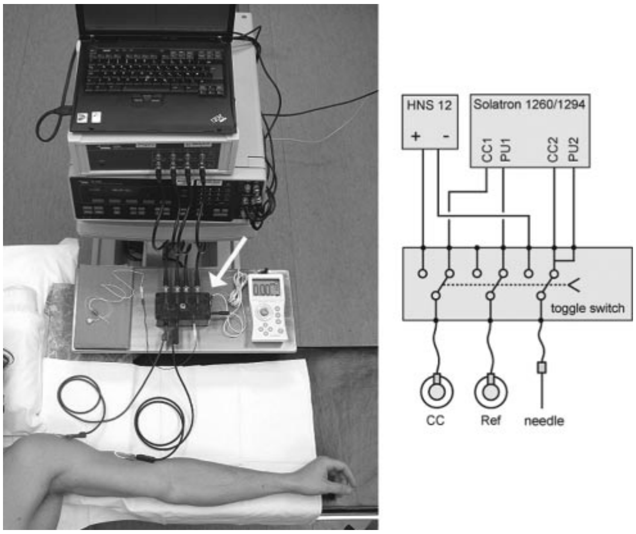

Figure 1. Connection diagram show the methodological setting for impedance measurements and nerve stimulation. The impedance measurement system (Solatron 1260/1294) and the nerve stimulator (HNS 12) were connected through a triple pole, double throw toggle switch (marked by an arrow in the photo) with the needle and the skin gel electrodes: CC1 and CC2—current carrying output, PU1 and PU2—measurement input, CC—current carrying skin electrode, Ref—reference electrode.

position), and about 2 cm proximal to the elbow fold, medial to the brachial artery (distal position). Aseptic preparation included skin asepsis with chlorhexidine 5%, a sterile transducer cover for the ultrasound probe (D-4570, Swemed Lab, Sweden), and sterile ultrasound gel (Aquasonic, Parker Laboratories, Fairfield, NJ).

A Solartron complex impedance measurement system (SI 1260/1294, Solartron Group PLC., Hampshire, UK) was connected through a triple pole, double throw toggle switch with the needle as the measurement electrode (Fig. 1). Two gel skin electrodes were used, one as a current carrying electrode (laterally, in the middle of the upper arm) and one as a reference electrode. This three-electrode setup ensured a unipolar measurement totally dominated by the impedance adjacent to the tip of the needle electrode.[3] A nerve stimulator (Stimuplex® HNS 12; B. Braun, Melsungen, Germany) was connected through the other throw of the toggle switch with the cathode to the needle and the anode to the current-carrying electrode.

The median nerve was scanned in the cross-sectional view, with the ultrasound probe perpendicular to the skin. A 35 mm, 25-gauge insulated needle with a 15° bevel (Stimuplex® D; B. Braun, Melsungen, Germany) was filled with 0.9% saline. In the axillary position the needle was inserted and advanced anteroposteriorly in the longitudinal axis of the ultrasound probe towards the median nerve. For ultrasound identification of the nerves, the outermost hyperechoic line was assumed to represent the epineurium. Using the integrated measuring system of the ultrasound unit, two markers were placed 5 mm apart to define a distance between the epineurium and the needletip. The needle was then advanced until the needletip had reached the 5 mm distance.

The impedance of the needle-tissue-electrode circuit was measured. Using the toggle switch, the measuring unit was disconnected and the nerve stimulator was then put in circuit. The stimulus impulse was set to a width of 0.3 ms at a frequency of 2 Hz. The current was slowly increased from 0 mA until motor responses were detected (flexion of wrist, fingers or thumb, or pronation), or to a maximum current of 5 mA. The current threshold needed to obtain a neuromuscular response was recorded. The impulse width was then set to 0.1 ms, and a new threshold for muscle response was established. Subsequently, the needle was repositioned to distances of 2.5 and 0 mm (nerve contact) and the measurements repeated. The measurements were repeated in the distal position (elbow), with the needle directed mediolaterally towards the nerve at distances of 5, 2.5, and 0 mm from the nerve. In each needle position, the type of tissue around the needletip was classified as either muscle or fat/connective tissue.

Ultrasound identification was based on the typical ultrasonographic characteristics of the tissue types. Muscle tissue has a longitudinal texture with hypo- or mixed echogenity, whereas fat and connective tissue have a more hyperechoic and homogeneous appearance. At needle-to-nerve contact, the tissue-type surrounding the needletip adjacent to the nerve (but not the epineurium) was used for classification. An ultrasound image was saved to document the needle positions.

Impedance Measurements

Impedance measurements depend on measurement frequency. Fourier analysis of the output signal from the Stimuplex® HNS 12 nerve stimulator at our institution's Clinical and Biomedical Engineering Department showed that the output voltage mostly contained low frequency components (<18,000 Hz). With small needle electrodes in tissue, low frequency measurements can give errors due to electrode polarization effects.[4] To reflect the frequency components of the nerve stimulator and reduce such errors, a measurement frequency at 7000 Hz was chosen. Complex impedance can be described in terms of resistance (real component) and reactance (imaginary component), both measured in ohm. In preliminary tests, the measured reactance gave no additional information or better results than the resistance alone. Therefore, we have chosen to use only the resistance of the measurements and refer to this as impedance throughout the article. The Stimuplex HNS 12 nerve stimulator, used in our study, has a display for calculated impedance. It was, however, used only for electrical nerve stimulation, whereas impedance values were solely measured by the SI 1260/1294 Solartron measurement system.

Table 1. Current Thresholds (mA) for Motor Stimulation of the Median Nerve

	5 mm	2.5 mm	0 mm
0.3 ms			
Axillary	3.75 (1.40–>5) mA	2.50 (0.80–4.00) mA	0.60 (0.28–1.60) mA
Elbow	2.00 (1.00–4.00) mA	1.00 (0.40–1.30) mA	0.36 (0.12–1.40) mA
0.1 ms			
Axillary	>5 (2.25–>5) mA	4.38 (1.40–>5) mA	0.90 (0.40–3.25) mA
Elbow	4.00 (1.80–>5) mA	1.90 (0.70–4.25) mA	0.70 (0.20–2.50) mA

Current thresholds (median and range) for nerve stimulation at nerve-to-needle distances of 5 mm, 2.5 mm, and 0 mm (nerve contact) in the axilla and at the elbow. The measurements were performed with impulse durations of 0.3 and 0.1 ms.

Statistics

Statistical analyses and sample size calculation were performed using Intercooled SATA for MAC, version 9 (Stata Corporation, College Station, TX). Because of missing values/censored data (when a motor response could not be obtained with the maximum current setting of 5 mA), some data are presented as median and range. When normal distribution was assumed, parametric methods were used and the results are presented as the mean with standard deviations. Paired *t*-tests were performed for comparison of the axillary and elbow measurements. Average values for each individual were used when repeated impedance measurements for different tissue types (muscle vs fat/connective tissue) or for different locations (axilla versus elbow) were compared with paired *t*-tests. Least squares linear regression was used to analyze the relation between impedance measurements and current thresholds. Multiple significance tests were done without multiplicity correction. Such correction is not considered necessary because of the exploratory study design.[5] *P* values smaller than 0.05 were considered statistically significant.

Sample-size:

Our primary hypothesis was that impedance might affect nerve stimulation. According to the studies of Tsui et al.,[6,7] an inverse relationship between impedance and current thresholds seemed likely. A sample size of 26 would have 80% power to detect a 25% proportion of the variance in current thresholds affected by impedance using least squares linear regression. To allow for missing data or dropouts, 30 volunteers were invited to take part in the study. One volunteer, however, failed to attend.

RESULTS

The 29 volunteers included 11 men and 18 women. Their mean age, weight, and height were 23 (SD 3) yr, 67 (SD 13) kg, and 174 (SD 11) cm. The median nerve was successfully identified and visualized in its complete course in the arm in all volunteers. At the elbow, nerve stimulation and impedance measurements were performed in all 29 volunteers. In the axilla, nerve stimulation and impedance measurements were performed in only 26 of the 29 participants. In one of the three volunteers who could not be examined, the median nerve was surrounded by blood vessels inhibiting advancement of the needle to the nerve. Measurements of distances and current thresholds were disturbed in the two other volunteers by muscle contractions, synchronous with local stimulation of the muscles.

The current thresholds for motor stimulation of the median nerve with impulse widths of 0.1 and 0.3 ms are shown in Table 1. The thresholds were significantly lower at the elbow compared to the axilla ($P < 0.001$, $P < 0.001$, $P = 0.024$) for needle-to-nerve distances of 5, 2.5, and 0 mm. Figure 2 illustrates the relationship between current thresholds with 0.3 vs 0.1

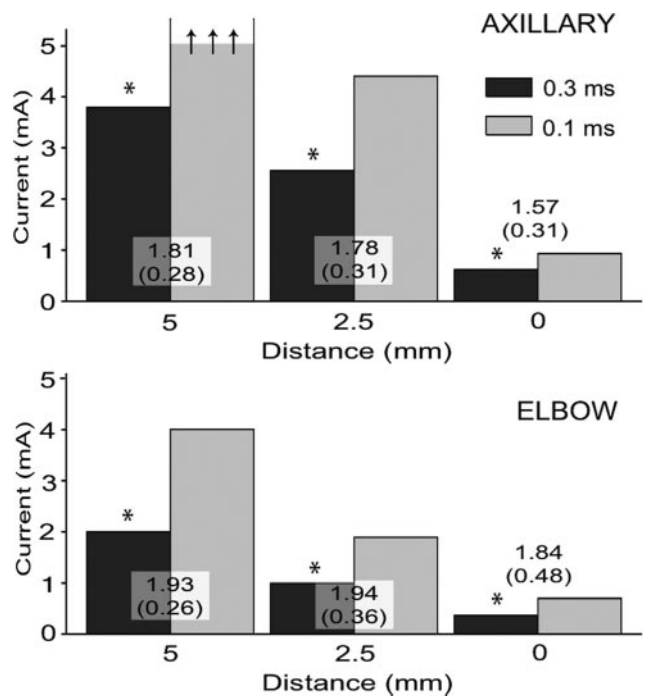

Figure 2. Median current thresholds to obtain neuromuscular responses with impulse durations of 0.3 and 0.1 ms. Nerve stimulation was performed in the axilla and at the elbow at needle-to-nerve distances of 5, 2.5, and 0 mm. The arrows represent median values above the maximum stimulating current of 5 mA. The ratios of the current thresholds with 0.1 vs 0.3 ms (calculated from paired measurements for each volunteer and needle position) are attached to the bars and referred to as mean (standard deviation). *A statistically significant difference to 0.1 ms impulse duration ($P < 0.001$).

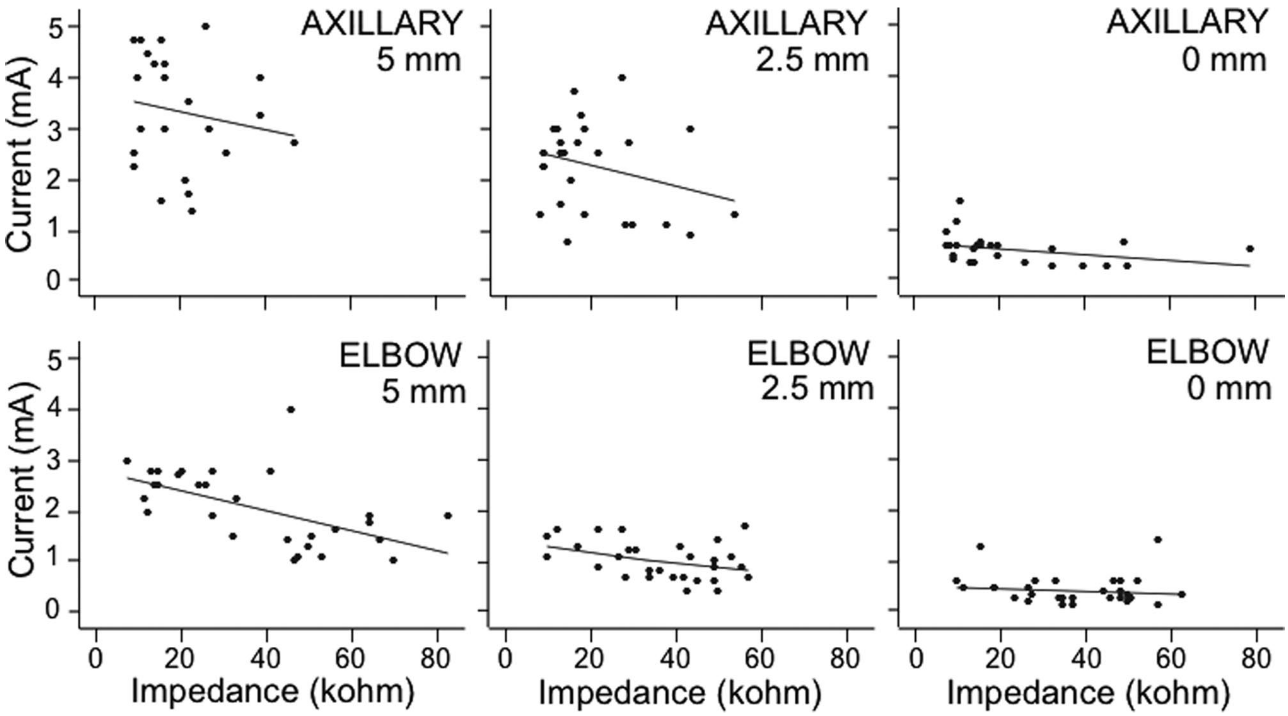

Figure 3. The Scatter plot shows the relation between current thresholds and measured impedance for the proximal (axilla) and distal part (elbow) of the median nerves at nerve-to-needle distances of 5, 2.5, and 0 mm. The line represents fitted values in a linear regression analyses. A significant inverse relation between current threshold and impedance measurements was found in the distal position (elbow) for 5 and 2.5 mm needle-to-nerve distances ($P = 0.001$ and $P = 0.036$).

ms impulse duration. The mean ratio for all measurements was 1.82 (SD 0.37). Failure to obtain neuromuscular responses with a maximum current of 5 mA occurred frequently when the nerve was stimulated with 0.1 ms impulse width (in 25 of 55 and 7 of 55 measurements at needle-to-nerve distances of 5 and 2.5 mm, respectively), but for only 3 of 55 measurements (at 5 mm distance) when 0.3 ms impulse duration was used. Therefore, subsequent analyses were performed only for data with 0.3 ms impulse durations.

The relation between current thresholds and impedance is shown graphically in the scatter plots (Fig. 3). *P* values and regression coefficients of a linear regression analysis are presented in Table 2. A significant inverse relation between current threshold and impedance measurements was found at the elbow for 5 and 2.5 mm needle-to-nerve distances.

In the axilla, the tissue type surrounding the needletip was identified as muscle in 64 (82%) and as fat/connective tissue in 14 (18%) of the measurements. In 86 (99%) of the measurements at the elbow, the needletip was positioned in fat/connective tissue and in only 1 (1%) of the measurements in muscle. The box plot in Figure 4 shows impedance measurements in different tissue types and different stimulating positions. Impedance was significantly lower ($P < 0.001$) when the needletip was in muscle (mean 20.6, SD 9.8 kohm) compared to fat/connective tissue (mean 35.4, SD 13.0 kohm). Accordingly, impedance values were significantly lower ($P < 0.001$) in the axilla (mean 21.1, SD 9.8 kohm) than at the elbow (mean 36.6, SD 13.4 kohm).

DISCUSSION

In the present study, electrical nerve stimulation of the median nerve was performed concurrently with impedance measurements of the tissue surrounding the needletip in 29 volunteers, whereas needle-to-nerve-distances were measured by ultrasound. A significant inverse relationship between impedance and current thresholds was found when measurements were performed at the elbow, with nerve-to-needle distances of 5 and 2.5 mm. In the axilla, only a tendency towards an inverse relationship was seen.

In the axilla, the needles were mainly positioned in muscle. Muscle tissue has inhomogeneous electrical properties with a directionally dependent conductivity parallel to the muscle fiber orientation.[8,9] Such electrical anisotropy may significantly affect the relationship between stimulating current and electrode-to-nerve distance in muscle tissue.[10] This could explain why a significant relationship between impedance and current thresholds could not be found for the axillary measurements. A relationship between impedance and current threshold could not be found when the needle was in direct contact with the nerve in either the axilla or at the elbow. For needle-to-nerve contact, it can be assumed that there are only small electrical potential differences between the needletip and the nerve. This could explain why tissue impedance did not affect nerve stimulation in this position.

Table 2. Linear Regression: Current Threshold – Impedance*

	Distance	*P*	Beta	R^2
Axillary	5 mm	0.428	−0.02	0.03
	2.5 mm	0.193	−0.02	0.06
	0 mm	0.128	−0.01	0.10
Elbow	5 mm	0.001	−0.02	0.32
	2.5 mm	0.036	−0.01	0.15
	0 mm	0.526	0.00	0.01

Relationship between treshold currents and impedance measurements.

The table shows *P*-values, Beta- and squared correlation coefficients for axillary and elbow measurements at nerve-to-needle distances of 5, 2.5, and 0 mm.

A significant inverse relation between current threshold and impedance was found at the elbow for 5 and 2.5 mm distances.

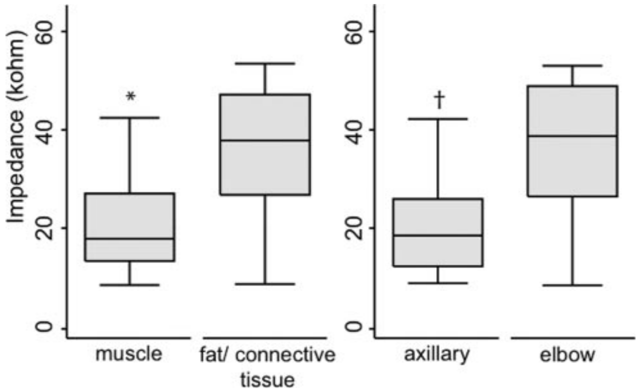

Figure 4. Impedance measurements (kohm) in different tissue types (muscle and fat/connective tissue) and different stimulating positions (axilla and elbow). The box plot denotes median, quartiles and range. *A statistically significant difference to fat connective/tissue ($P < 0.001$). †A statistically significant difference to the elbow ($P < 0.001$).

When the median nerve was stimulated in the axilla, significantly higher current thresholds were found than at the elbow. The significantly lower impedance of muscle tissue in the axilla may have caused these differences. In our previous study on nerve stimulation in the elbow region, the current thresholds were significantly higher for the radial nerve than for the ulnar nerve.[1] The ulnar nerve was surrounded by connective tissue and subcutaneous fat while the radial nerve was in contact with the brachioradial and the brachial muscles.

Tsui et al.[6,7] demonstrated that the current thresholds were decreased or increased by injecting nonconducting dextrose 5% solution or conductive saline/local anesthetic, respectively, through the stimulation needle. In our study, the current thresholds were affected by tissue impedance in a similar way. A highly conductive tissue near the needle tip can lead the current in undesired paths away from the nerve. Tsui et al.[6] demonstrated this in their model where a significant portion of the current was dispersed away from the tip proximally along the needle.

The results of our study indicate that current levels should be adjusted depending on the impedance of the tissue. Nerve stimulators with a display for electrical impedance are commercially available. For the purpose of our study, the accuracy of such integrated measurement devices did not seem appropriate. However, nerve stimulators with integrated impedance calculation should give valuable information in a clinical setting. When impedance measurement is not available, anatomical knowledge of the tissue surrounding a nerve may still help in estimating the conductive properties. Increased current settings may be advisable when the stimulating needle is advanced through low impedance muscle tissue compared to fat or connective tissue with high impedance.

Nerve stimulation with an impulse width of 0.3 ms was used to obtain neuromuscular responses at longer needle-to-nerve distances. Clinically, a 0.1 ms impulse width is more commonly used for electrical motor stimulation.[11,12] A set of measurements with 0.1 impulse widths was performed to relate the current thresholds to the common clinical situation. A mean ratio of 1.82 was found for our measurements of current thresholds with 0.1 vs 0.3 ms impulse duration. The effect of different impulse durations on nerve stimulation has been investigated in several studies.[12–14] However, ratios for the current thresholds for peripheral blocks have not, to our knowledge, been published. Our results indicate that current settings should be approximately doubled when using 0.1 ms compared to 0.3 ms impulse durations, to obtain equivalent neuromuscular responses.

Our study has several limitations. Ultrasound is a highly observer-dependent method; both identification of anatomical structures and distance measurements have a subjective component. For the measurements of small distances with ultrasound, Kiserud et al.[15] demonstrated interobserver variations between 0.1 and 0.38 mm. Furthermore, ultrasound identification of the epineurium might also be challenging. Thus, by using ultrasound alone we can not be sure if the needletip actually was in contact with the epineurium at the 0 mm needle-to-nerve distance.

Our study investigated the effect of impedance on current threshold. Other factors, including the distribution of motor and sensory fibers[16] or the proportion of connective tissue, ranging from 30% to 75% within the course of a peripheral nerve,[17] could also affect nerve stimulation. We investigated the effect of tissue impedance on current thresholds for the median nerve only; impedance may be different at other locations and the importance of impedance for nerve stimulation may vary for different nerves. Further studies are warranted to examine the effect of tissue impedance for different nerves.

In conclusion, our results show an inverse relationship between impedance measurements and current thresholds. Our results indicate that current settings used for nerve stimulation may require adjustment based on the tissue type and impedance. Further studies should be performed to investigate the clinical impact of our findings.

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