

Nerve Stimulators Used for Peripheral Nerve Blocks Vary in Their Electrical Characteristics

Admir Hadzic, M.D., Ph.D.,* Jerry Vloka, M.D., Ph.D.,* Nihad Hadzic, M.C.E.,† Daniel M. Thys, M.D.,‡ Alan C. Santos, M.D., M.P.H.‡

Background: Nerve stimulation with a low-intensity electrical current has become a vital part of the performance of peripheral nerve blockade. The purpose of this study was to compare the accuracy and characteristics of peripheral nerve stimulators used in clinical practice in the United States.

Methods: Fifteen peripheral nerve stimulators were fitted with fresh batteries and set to deliver currents ranging from 0.1 to 4.0 mA into a series of high-tolerance resistance loads ranging from 1 to 100 k Ω . The current output, stimulus duration, morphology, frequency, and maximum voltage output were studied using a factory-calibrated oscilloscope.

Results: All peripheral nerve stimulators performed uniformly well when set to deliver currents of 1.0 mA or more into a standard resistance load of 1 or 2 k Ω . However, at lower currents, the median error (%) increased from 2.4 (–5–144%) at 0.5 mA to 10.4 (–24–180%) at 0.1 mA into a 1 k Ω load. The morphology of the stimulus was characterized by a regular monophasic square pulse at current outputs of up to 1 mA and at a resistance of 1 k Ω . The stimulus waveform became particularly distorted as the impedance load was increased. The duration of the default stimulus set by the manufacturer varied from 34.8 to 460 μ s among the peripheral nerve stimulators tested. The maximum voltage output ranged from 7.4 to 336 Volts.

Conclusions: Nerve stimulators used for regional anesthesia vary greatly in accuracy of current output and in manufacturer-selected electrical characteristics (e.g., current duration, stimulating frequency, maximum voltage output).

LOCALIZING peripheral nerves during the initiation of nerve blocks using stimulation with a low-intensity electrical current has become common practice in regional anesthesia. The increasing use of peripheral nerve blocks has been associated with an increased demand for and greater availability of peripheral nerve stimulators. The ability of a peripheral nerve stimulator to evoke a motor response depends on the distance of the stimulus from the nerve (*i.e.*, the needle-to-nerve distance), as well as the intensity and duration of the current used.¹ Most authors recommend obtaining a motor response with a current less than or equal to 0.5 mA before injecting a local anesthetic.² Stimulation at currents

higher than 0.5 mA may result in failure of the block because the needle is too far from the nerve, whereas injection after stimulation at a current lower than 0.1 mA may risk nerve damage because of the possibility of an intraneuronal injection of local anesthetic.^{3,§}

The purpose of this study was to evaluate the characteristics and accuracy of the current delivered by peripheral nerve stimulators in common clinical use in the United States.

Materials and Methods

Peripheral nerve stimulators made available to us through loans from manufacturers, distributors, or colleagues were bench tested in our laboratory. The characteristics of the current output, the stimulating frequency, and the ability of the unit to accurately deliver a selected current were evaluated. All stimulators were in routine clinical use and had valid inspection seals from their respective biomedical engineering departments. Immediately prior to study, all stimulators were fitted with fresh, industrial-grade batteries and set to deliver currents of 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, and 4.0 mA into preselected resistance loads. Each current level was tested with increasing impedance loads of 1, 2, 5, 10, 20, 50, and 100 k Ω (Resistance Substitution Set Model 236A; Phipps and Bird, Inc., Richmond, VA). This range of resistance loads was chosen in order to simulate both the bioimpedance of a normal patient (1 to 2 k Ω),⁴ as well as the greater impedance that may be associated with dry skin, desiccated electrodes, or poor skin-electrode conductance (contact; > 2 k Ω).^{5,6} All measurements were made by an engineer who was unaware of the make and model being tested. The sequence of measurements was repeated three times, and the average of three measurements was reported for each current at each resistance level. The output of the peripheral nerve stimulator was determined using a factory-calibrated oscilloscope (Fluke DigiMeter 123; Fluke Corp., Everett, WA). The current output (I ; mA) was calculated using the equation $I = U/R$, where U is the voltage measured (Volts) and R (Ω) is the selected resistance. The output signal of each nerve stimulator was stored on a computer hard drive and analyzed using a commercially available software package (Flukeview[®] SW90W Software, version 2.1; Fluke Corp., Everett, WA). The following variables were measured: signal amplitude (peak to peak maximum value of a signal output), stimulus duration, and signal morphology (variation of the signal amplitude from the

* Associate Professor, ‡ Professor, Department of Anesthesiology, St. Luke's-Roosevelt Hospital Center. † Electronic Engineer, IBM, Poughkeepsie, New York.

Received from the Department of Anesthesiology, St. Luke's-Roosevelt Hospital Center, College of Physicians and Surgeons of Columbia University, New York, New York. Submitted for publication June 12, 2002. Accepted for publication October 28, 2002. Support was provided solely by institutional and/or departmental sources.

Address reprint requests to Dr. Hadzic: Department of Anesthesiology, St. Luke's-Roosevelt Hospital Center, Travers 701, 1111 Amsterdam Avenue, New York, New York 10025. Address electronic mail to: ah149@columbia.edu. Individual article reprints may be purchased through the Journal Web site, www.anesthesiology.org.

§ New York School of Regional Anesthesia Web site. Available at: <http://www.nysora.com>. Accessed October 18, 2001.

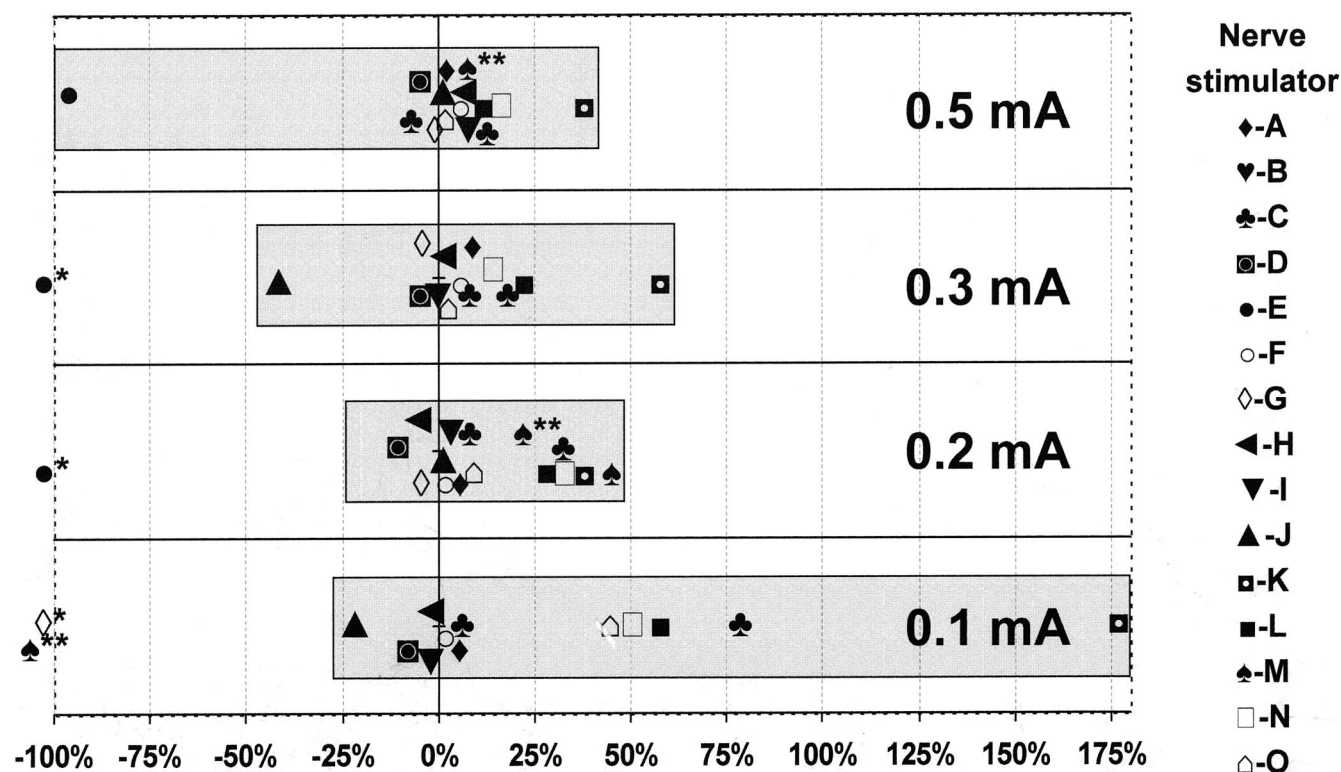


Fig. 1. Percent error for individual stimulators calculated from the measured current *versus* the selected current at an impedance load of 1 k Ω (N = 15). *The stimulator could not deliver a stimulus in this range. **The stimulator delivered current in incremental steps of 0.20 mA

expected monomorphic square wave throughout the duration of the stimulus). The *rise time*, the time required for the signal to increase from 0.1 V_{min} (near minimal value of the signal voltage) to 0.9 V_{max} (submaximal value of the signal voltage), and the *decay time*, the time required for the signal to decrease from 0.9 V_{max} to 0.1 V_{min}, were determined from the digitally stored measurements of the stimulus. The maximum voltage output was determined by setting the unit to deliver the highest current output possible and then by increasing the resistance load until the voltage output reached a plateau.

Statistical Analyses

The percent error was determined by comparing the measured currents with the preset currents that were preselected for the study. For instance, if a peripheral nerve stimulator was set to deliver a current of 1.0 mA but delivered a current of 0.7 mA, the percent error for this stimulator was -30%. The data on percent error are presented as median and range. As percent error was not normally distributed, the nonparametric equivalent of a two-way analysis of variance with repeated measures (Friedman test) was used to assess differences in ranked percent error at the preset currents. Similarly, the Wilcoxon signed-rank test was used to assess differences in rise and decay times (μ s) at resistances of 1 and 50 k Ω .

Statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS for Windows, version 5.0.2; SPSS Inc., Chicago, IL). $P \leq 0.05$ was considered to be statistically significant.

Results

Fifteen peripheral nerve stimulators were tested. All units performed within 5% error when set to deliver a current of 1.0 mA or more into an impedance load of 1 or 2 k Ω . However, at lower currents, the median error increased from 2.4% (-5-144%) at 0.5 mA to 10.4% (-24-180%) at 0.1 mA into a 1-k Ω load (fig. 1). The actual current delivered by four nerve stimulators varied by more than 30% when set to deliver a current of 0.3 mA and by nearly 90% at a current of 0.1 mA. One nerve stimulator was unable to deliver a current of less than 0.5 mA.

For all units, the frequency and duration of the stimulus were accurate within 5% of the values specified by the manufacturer. However, eight stimulators delivered a current at 1 Hz (one stimulus per second), whereas seven stimulators used 2 Hz (two stimuli per second). Some nerve stimulators (A, D, F, G, H) also had the capability for the operator to select the stimulating frequency (1-5 Hz; table 1). The duration of the stimulating

Table 1. Make and Models of Tested Nerve Stimulators

Stimulator	Model	Circuitry	Stimulating Frequency, Hz	Manufacturer	Serial No.
A	Stimuplex HNS11	CC	1 or 2	B. Braun Medical Inc., Bethlehem, PA	NA
B	TOF-WATCH	CV	1	Organon Teknika B.V., Boxtel, The Netherlands	13-1998020
C	Tracer II Model NL-2	CC	2	Life-Tech, Inc., Stafford, TX	0C0600014
D	Stimuplex DIG	CC	1 or 2	B. Braun Medical Inc., Bethlehem, PA	4567
E	Tracer Model NL-1	CV	1	Life-Tech, Inc., Stafford, TX	PI 00835
F	POLYSTIM	CC	1 or 2	te me na SARL, Bondy, France	048-200
G	Neuro-Trace II	CV	1 to 5	HDC Corp., San Jose, CA	303440
H	MultiStim PLEX	CC	1 or 2	Pajunk, Gesingen, Germany	1039
I	MultiStim VARIO	CC	1 or 2	Pajunk, Gesingen, Germany	1209
J	MaxiStim Model ST6	CC	1	Life-Tech, Inc., Stafford, TX	01867
K	Digistim II	CV	1	Neuro Technology, Houston, TX	NA
L	Digistim III	CV	1	Neuro Technology, Houston, TX	NA
M	Innervator NS272J	CC	1	Fischer & Paykel, Auckland, New Zealand	2000-27JUU00880
N	EZstim Model ES100	CC	1	Life-Tech, Inc., Stafford, TX	00318
O	DualStim DX NS-2CA	CV	1	Life-Tech, Inc., Stafford, TX	P04319

CC = constant current; CV = constant voltage

current (programmed by the manufacturer) also varied among the stimulators tested, with the shortest stimulus measured at 34.8 μ s and the longest at 460 μ s (fig. 2). In addition, two units (A, F) had a programmable feature that allowed the operator to choose from 100, 300, or 1,000 μ s as the duration of the stimulus.

The morphology of the stimulus was characterized, for the most part, by a regular monophasic square pulse at a current output of 1 mA into a load of 1 k Ω (fig. 3). However, as the resistance load increased, the morphology of the stimulus became progressively more distorted. Rise and decay times (μ s) were both markedly higher at 50 k Ω than at 1 k Ω (table 2; Wilcoxon *P* values < 0.001). At 50 k Ω , rise and decay times were especially high for several of the nerve stimulators (*i.e.*, rise times for G and J, decay times for B, G, J, and M). However, the significance of the Wilcoxon signed-rank test did not change appreciably when these nerve stimulators were removed from the analyses (from *P* < 0.001 to *P* < 0.003 for difference in decay time).

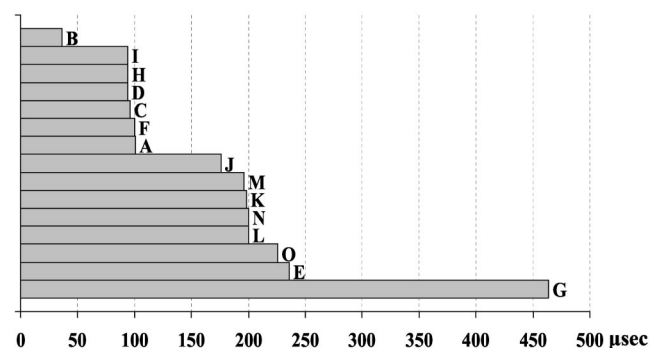


Fig. 2. Duration of the stimulating current measured from the individual peripheral nerve stimulators tested (N = 15). *Differences in current duration among the individual nerve stimulators are not a result of inaccuracy of the studied units but of the intended manufacturers' designs.

The maximum voltage output varied among the units tested as a function of the load and ranged from 7.4 to 336 Volts (*P* \geq 0.001; fig. 4).

Discussion

Nerve stimulation used to localize a nerve prior to local anesthetic injection has become common practice for initiating peripheral nerve blocks. Consequently, many different models of peripheral nerve stimulators are now available for clinical use in the United States. Our study indicates that peripheral nerve stimulators perform well when tested at levels specified by their respective manufacturers (usually 1.0 mA into a load of 1 or 2 k Ω). However, at the lower intensity currents that are now used in clinical practice,^{2,6} selected and delivered stimulating currents can be widely discrepant among the peripheral nerve stimulators that are in routine clinical use. In addition, units' other electrical characteristics can vary.

Accuracy

The capability of a peripheral nerve stimulator to accurately deliver a specified current is important for the success of peripheral nerve blocks and the prevention of complications.¹ The ability of a peripheral nerve stimulator to stimulate a nerve at a selected current intensity depends on the proximity of the needle to the nerve.¹ For instance, Pither *et al.*¹ reported that a motor response could only be elicited with a stimulating current of low intensity (0.1 mA) when the needle was in contact with the nerve, whereas a current of a much higher intensity (2.5 mA) was required to stimulate the nerve when the needle was 2.5 cm away. Thus, it would seem particularly important that nerve stimulators used for regional anesthesia be able to deliver an accurate current in the range of electrical output now recommended for

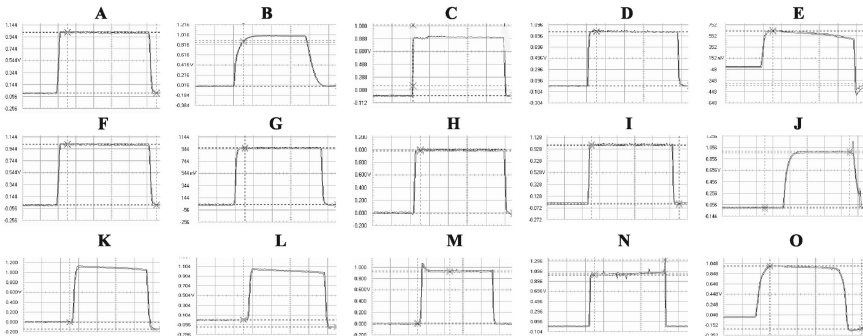


Fig. 3. Morphology of the stimulus delivered by individual units when set at a current of 1.0 mA and at an impedance load of 1 kΩ (N = 15).

peripheral nerve blocks, namely 0.1–0.5 mA.^{2,6–9} However, in our study, the accuracy of nerve stimulators, while good at the levels of current specified by the manufacturers, was lowest in the range of currents now used for peripheral nerve blocks. Our data are in agreement with findings from a smaller study conducted in Australia in which only three of six units tested were able to deliver a current of 0.3–3.0 mA with 20% accuracy.⁷ In contrast to the aforementioned study, we chose to evaluate performance at lower currents (< 0.3 mA), which are more applicable to contemporary clinical practice.^{8,9} Indeed, in current practice, stimulating currents of 0.1–0.5 mA are commonly used in order to ensure that the needle is in close proximity to the nerve before injecting a local anesthetic.^{2,8,9} A nerve stimulator that delivers less current than what the operator has selected may lead the operator to continue advancing the needle toward the nerve when, in fact, the needle is already in close proximity to the nerve. This, in turn, may result in mechanical injury or even intraneuronal injection of local anesthetic.¹⁰ These risks may be increased further when peripheral nerve blocks are performed in heavily sedated or anesthetized patients who

may not be able to perceive a severe paresthesia as a warning sign of impending neuronal injury.^{10,11} In contrast, a nerve stimulator that delivers a current higher than the selected current may result in injection of local anesthetic when the needle is remote from the nerve, thereby increasing the chance of a failed block.¹ Lastly, the reproducibility and success of nerve block techniques reported in clinical studies may vary when different makes or models of peripheral nerve stimulators are used. Although the optimum accuracy of electrical output was not determined in our study, it would seem prudent that peripheral nerve stimulators be particularly exact at the low currents used in clinical practice (≥ 0.5 mA).

Stimulus Duration

The duration of the stimulating current varied among the units studied. This is important because there are two electrophysiologic variables that may affect stimulation of a nerve with a current: the *rheobase*, which is the minimum current required to stimulate a nerve with a long pulse, and the *chronaxie*, which is the duration of the stimulus required to stimulate the nerve at twice the rheobase.^{1,12} The chronaxie of peripheral nerves may vary. For instance, the large, heavily myelinated A α motor fibers depolarize more readily with a current of short duration (50–100 μ s), whereas the smaller, unmyelinated C fibers preferentially depolarize with a stimulus of long duration (≤ 400 μ s).¹ Thus, the ability of a nerve

Table 2. The Rise and Decay Times of Peripheral Nerve Stimulators Set to Deliver 1 mA into the 'Normal' Load of 1 kΩ and into an Abnormally High Impedance Load (50 kΩ)				
	Rise Time, μsec		Decay Time, μsec	
Stimulator	1 kΩ	50 kΩ	1 kΩ	50 kΩ
A	3.2	32	3.2	52
B	5.2	10.4	6.4	93.6
C	0.8	18.4	0.8	38.4
D	1.8	25.6	1.8	44
E	2	12	2	20
F	3.0	34	2.8	52
G	4	260	8	304
H	0.8	36	0.8	12.8
I	1.0	36	1.0	12.8
J	16	160	14	896
K	6	26	4	16
L	6	14	4	12
M	2	36	2	158
N	2	48	2	30
O	22	32	16	20
Median	3.0	32.0	2.8	38.4
	<i>P</i> < 0.001		<i>P</i> < 0.001	

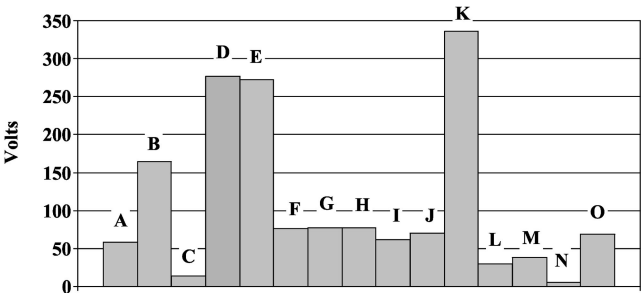


Fig. 4. Maximum voltage output (V) of individual units at abnormally increased impedance loads (≤ 50 kΩ; N = 15). *Differences in current duration among the individual nerve stimulators are not a result of inaccuracy of the studied units but of the intended manufacturers' designs.

stimulator to elicit a motor response rather than a noxious stimulus depends largely on its ability to deliver a stimulus of small intensity and short duration in order to depolarize the larger A α fibers rather than the smaller C fibers. Furthermore, laboratory studies have demonstrated that stimuli of short duration are more precise in predicting the needle-nerve relationship.¹³ Although there are no clinical studies, it is possible that variations in stimulus duration may affect patient comfort, as well as the success and safety of peripheral nerve blocks.

Stimulus Morphology

The stimulating current ideally should be delivered in the form of a monomorphic pulse, with a rapid increase in current output followed by a plateau of constant intensity for the duration of the stimulus and then by a rapid decay. However, the morphology of the stimulus varied among the units tested and became particularly distorted with increasing current and voltage output. The most variable aspects of the stimulus morphology were the rise and decay times, which, in some instances, accounted for 20% or more of the total duration of the stimulus. The effects on rise and decay times were particularly pronounced as the resistance load was increased, such as could occur clinically in patients with very dry skin or due to a desiccated surface electrode.⁵ Although the aforementioned changes in stimulus morphology may decrease the effective energy delivered to the nerve (energy [nc] = current [mA] \times duration [μ s]),⁶ it is currently unclear how this could potentially affect nerve stimulation.

Frequency of Stimulus

The frequency of the stimulating current varied between 1 and 5 Hz. This may have clinical implications because there are longer pauses between stimuli at 1 as compared to 2 Hz or more. For that reason, advancement of the needle should be performed at a slower rate when using a stimulator with a 1-Hz frequency in order to avoid missing or inadvertently impaling the nerve.

Maximum Voltage Output

Most newer peripheral nerve stimulators use technology based on constant current circuitry, which senses the difference between the current set by the user and the actual current delivered by the unit. When the stimulating current sensed by the unit is lower than the selected current, the circuitry in these peripheral nerve stimulators automatically compensates for the lower current by increasing the voltage output. This scenario may arise in clinical practice when an abnormally high impedance is encountered due to excessively dry skin or to a desiccated surface electrode.⁵ Under these circumstances, a voltage as high as 336 V may be delivered by some peripheral nerve stimulators in order to maintain a selected level of current. This may be painful to the

patient because, despite delivering a low stimulating current, excessive voltage is applied to the nerve over a very small area by the tip of the stimulating needle.^{5,6} In addition, high-output peripheral nerve stimulators (e.g., 70 mA or 500 V) used for monitoring neuromuscular blockade have been reported to cause skin burn under certain circumstances.¹⁴ Although a similar complication has not been reported after the use of nerve stimulators for nerve blockade, it would seem prudent to avoid applying such high current or voltage output in the vicinity of the nerves.

A potential weakness of our study is that only one unit of each model was tested. Consequently, it is possible that the performance of some units may have deteriorated with months or years of clinical use. However, at the time of the experiment, all stimulators were in clinical use and had valid inspection seals from their respective biomedical engineering departments. This suggests that the performance of these peripheral nerve stimulators was within acceptable limits when tested according to the recommendations of their respective manufacturers (usually 1.0 mA into a load of 1 or 2 k Ω). These higher current levels most likely are based on earlier studies of peripheral nerve block techniques.^{15,16} However, our findings suggest that peripheral nerve stimulators also should be tested for their accuracy at currents of 0.1–0.5 mA, which are now used in clinical practice.^{2,6,8,9}

In conclusion, our results indicate that there is disparity in the accuracy and characteristics of the stimulating current delivered by different peripheral nerve stimulators in clinical use. Further studies are required to determine how these differences can potentially affect success rate and patient comfort and safety when peripheral nerve stimulators are used to localize nerves. In addition to routine testing of units at manufacturer-recommended levels, peripheral nerve stimulators used in regional anesthesia also should be evaluated at the lower range of currents that are more applicable to modern clinical practice.

The authors thank Kevin Sanborn, M.D. (Associate Director of Anesthesia, Department of Anesthesiology, St. Luke's-Roosevelt Hospital Center, College of Physicians and Surgeons of Columbia University, New York, New York), for his help in preparing this manuscript.

References

1. Pither CE, Raj PP, Ford DJ: The use of peripheral nerve stimulators for regional anesthesia. A review of experimental characteristics, technique, and clinical applications. *Reg Anesth* 1985; 10:49–58
2. Brown DL: Atlas of Regional Anesthesia. Philadelphia, WB Saunders, 1992, p 11
3. Selander D: Peripheral nerve injury after regional anesthesia, *Complications of Regional Anesthesia*, 1st edition. Edited by Finucane BT. Philadelphia, Churchill Livingstone, 1997, pp 105–15
4. Valentinuzzi EM: Bioelectrical impedance techniques in medicine. Part I: Bioimpedance measurement. *Crit Rev Biomed Eng* 1996; 24:223–55
5. Vloka JD, Hadzic A, Thys DM: Peripheral nerve stimulators for regional anesthesia can generate excessive voltage output with poor ground connection. *Anesth Analg* 2000; 91:1306–13

6. Pinnock CA, Fischer HBJ, Jones RP: Peripheral nerve blockade, *Peripheral Nerve Blockade*, 1st edition. Edited by Pinnock CA, Fischer HBJ, Jones RP. Edinburgh, Scotland, Churchill Livingstone, 1996, pp 12-3
7. Bathram CN: Nerve stimulators for nerve localization—are they all the same? *Anaesthesia* 1997; 52:761-4
8. Urney WF, Stanton J: Inability to consistently elicit a motor response following sensory paresthesia during interscalene block administration. *ANESTHESIOLOGY* 2002; 96:552-4
9. Choyce A, Chan VW, Middleton WJ, Knight PR, Peng P, McCartney CJ: What is the relationship between paresthesia and nerve stimulation for axillary brachial plexus block? *Reg Anesth Pain Med* 2001; 26:100-4
10. Auroy Y, Narchi P, Messiah A, Lawrence L, Rouvier B, Samii K: Serious complications related to regional anesthesia. *ANESTHESIOLOGY* 1997; 87:479-86
11. Benumof JL: Permanent loss of cervical spinal cord function associated with interscalene block performed under general anesthesia. *ANESTHESIOLOGY* 2000; 93:1541-4
12. Holsheimer J, Dijkstra EA, Demeulemeester H, Nuttin B: Chronaxie calculated from current-duration and voltage-duration data. *J Neurosci Methods* 2000; 97:45-50
13. Ford DJ, Pither C, Raj PP: Comparison of insulated and uninsulated needles for locating peripheral nerves with a peripheral nerve stimulator. *Anesth Analg* 1984; 63:925-8
14. Lippmann M, Fields WA: Burns of the skin caused by a peripheral-nerve stimulator. *ANESTHESIOLOGY* 1974; 40:82-4
15. Zeh DW, Katz RL: A new nerve stimulator for monitoring neuromuscular blockade and performing nerve blocks. *Anesth Analg* 1978; 57:13-7
16. Chapman GM: Regional nerve block with the aid of a nerve stimulator. *Anaesthesia* 1971; 27:185-93