Conductive Differences in Electrodes Used with Transcutaneous Electrical Nerve Stimulation Devices
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Conductive Differences in Electrodes Used with Transcutaneous Electrical Nerve Stimulation Devices

The purpose of this study was to document conductive differences among commercially available electrodes used with transcutaneous electrical nerve stimulation (TENS) devices. Impedance within a model system involving a human subject was calculated from oscilloscopic tracings of the pulse waveform for each of 25 different electrode types. Impedance values ranged from 1,000 to 7,800 Ω. Possible reasons for these differences are discussed. The observation that electrodes vary in their impedance and can thereby affect the stimulus applied to the skin raises the question of whether electrode choice might affect the clinical effectiveness of TENS. Attention is drawn to the skin electrodes as a variable that may affect the results of clinical and basic studies involving TENS. [Nolan MF. Conductive differences in electrodes used with transcutaneous electrical nerve stimulation devices. Phys Ther. 1991;71:746-751.]

Key Words: Electrode, Impedance, Transcutaneous electrical nerve stimulation.

Transcutaneous electrical nerve stimulation (TENS) is frequently used in the symptomatic management of acute and chronic pain conditions. Its attractiveness as a therapeutic modality is based in part on its simplicity and the ease with which it can be used.

An important component of the TENS system is the skin electrode. Early TENS electrodes were fashioned from silicone rubber impregnated with carbon particles. Effective transmission of the electrical pulse necessitated the use of a coupling agent, typically a gel, and tape was required to secure the electrodes in place. Contemporary electrodes use newly developed polymers as the conducting medium, and many are prepackaged with hypoallergenic adhesive materials. These newer electrodes are less messy and easier to apply and remove than the carbon-rubber-gel electrodes. The newer electrodes, therefore, offer features that may significantly affect patient compliance.

Many contemporary electrodes can be used interchangeably with different TENS devices. Adapters are also available that allow an even greater number of stimulator-electrode combinations, the claimed value of which is the ability to create custom-made stimulating systems, individually designed to meet the specific needs of the patient or the requirements of the clinical situation.

The ability to use various types of electrodes with a particular TENS device prompted me and my colleagues at the University of South Florida (Tampa, Fla) to question whether the therapeutic effectiveness of TENS might be influenced by the choice of electrodes. To answer this question, we thought it necessary to first understand how electrodes differ and how particular types of electrodes might influence the electrical pulse delivered to the skin. Although these concerns have been addressed for electrocardiographic and electroencephalographic electrodes, we could find no reports in the literature that directly addressed these issues for TENS electrodes. The purpose of this initial study, therefore, was to document whether differences existed among commercially available TENS electrodes based on calculations of impedance in a model system us-
ing a human subject. The ability to distinguish electrodes based on their conductive properties might be helpful in identifying and selecting specific types of electrodes that might be appropriate for use in studies dealing more directly with the question of clinical efficacy.

Method

Twenty-five different commercially available electrodes were obtained for use in this study (Appendix). Some were obtained as part of a TENS device package. Electrodes obtained in this way were either designed specifically for use with a particular TENS device or, more commonly, were the flexible carbon-rubber type. Other electrodes were obtained directly from manufacturers of TENS supplies. These electrodes were typically marketed as being appropriate for use with more than one type of TENS device.

All measurements were performed on a single nondisabled, adult, male subject, who reported being free from cutaneous, vascular, or nervous system disease. The subject in this study was familiar with the sensation of TENS and consented to participate in this initial study.

In accordance with routine skin preparation procedures, the skin on the volar surface of the subject’s left forearm and wrist was cleansed with an alcohol wipe and allowed to air dry. A matching pair of electrodes was then applied, one electrode on the skin over the median nerve in the cubital fossa and the other electrode on the skin over the median nerve at the wrist. Self-adhesive electrodes were affixed according to the manufacturers’ instructions. Carbon-rubber electrodes were coated with a thin layer of gel (Appendix), which was evenly spread to completely cover the skin contact surface, and the electrodes were secured in place by means of a comfortably fitting 2.54-cm (1-in) Velcro® strip. Excess gel was wiped away after the lead wires were connected.

Stimulation was delivered using a single channel of a constant-current TENS device. Because the stimulator used in this study delivered an asymmetrical biphasic pulse, each electrode was cathodal for a period of time during the pulse cycle and anodal during the remaining time. For the purpose of this study, the electrode demonstrating a negative deflection on the oscilloscope at the beginning of the pulse cycle was attached proximally on the subject’s forearm.

A dual-channel oscilloscope was used to monitor both current and voltage waveforms. Current was measured by determining voltage drop across a resistor placed in series with one lead of the TENS device. Voltage was measured directly from the oscilloscope. Stimulator output was initially applied to a 1,000-Ω resistor to preset the TENS device to deliver a 200-microsecond pulse of 10 mA at a frequency of 85 Hz, output settings within the range of those commonly used in clinical practice. Changes in peak voltage from preset values were measured from oscilloscopic tracings when the current was redirected by means of a switch from the resistor to the subject. Impedance in the model system from the electrodes and the body was then calculated by dividing the peak voltage dropped by the current.

Only one pair of electrodes was tested each day to eliminate effects resulting from cutaneous reactions to the conducting media, adhesives, or stimulating current. Each electrode pair was tested on two separate occasions, with all 25 electrode pairs being tested once before the second round of trials was begun. New electrodes were used for each test session. All experiments were performed at the same time each day in a temperature- and humidity-controlled environment (temperature was maintained at 22°-23°C, and humidity was maintained at 66%-70%).

In preliminary experiments carried out to develop and test the model system, two effects evolved gradually when stimulation lasted for more than 10 minutes. These effects were a reduction in the subject’s perceived intensity of stimulation and changes in measured voltage. Perceptual changes can be attributed to stimulation effects on cutaneous receptors or peripheral nerve conductivity, to the activation of mechanisms within the central nervous system, or possibly to some combination of these effects. Voltage changes suggest the occurrence of physical or chemical changes in the skin, the electrode-conducting medium complex, or both, that alter resistance to the flow of current. To eliminate these effects, all measurements were completed within the first 10 seconds following the onset of stimulation.

Results

Impedance measurements for both trials with each pair of electrodes tested in the model system are presented in the Table. Measured values ranged from 1,000 to 7,800 Ω. For descriptive purposes, electrodes were classified into three groups based on naturally occurring breaks in the calculated impedance values. The low-impedance group demonstrated values ranging between 1,000 and 1,900 Ω, the medium-impedance group showed values of 2,100 to 4,400 Ω, and the high-impedance group was characterized by impedance measurements of ≥5,000 Ω. These values do not represent the impedance of the electrodes themselves, but rather impedance within the model system used in this study.
Table. Impedance Measurements (in Ohms) for Two Separate Trials with Each Electrode Pair

<table>
<thead>
<tr>
<th>Low-Impedance Group</th>
<th>Medium-Impedance Group</th>
<th>High-Impedance Group</th>
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<tbody>
<tr>
<td>Electrode Number</td>
<td>Trial 1</td>
<td>Trial 2</td>
</tr>
<tr>
<td>8</td>
<td>1,200</td>
<td>1,900</td>
</tr>
<tr>
<td>9</td>
<td>1,200</td>
<td>1,100</td>
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<tr>
<td>13</td>
<td>1,000</td>
<td>1,000</td>
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<tr>
<td>14</td>
<td>1,600</td>
<td>1,600</td>
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<td>15</td>
<td>1,400</td>
<td>1,600</td>
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<td>16</td>
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<td>1,400</td>
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<tr>
<td>17</td>
<td>1,200</td>
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<tr>
<td>20</td>
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With the exception of electrodes 8 and 15, the electrodes in the low-impedance group were made of carbon-rubber and used either gel or karaya as the conducting medium. Electrode 8 was a pregelled, self-adhesive electrode, and electrode 15 used a water-moistened, synthetic conductive adhesive as a coupling agent. Electrode 8 was the only single-use electrode in the low-impedance group.

The medium-impedance group of electrodes was characterized by greater diversity with regard to conducting medium. Electrode 2 was a pregelled, self-adhesive electrode. Electrode 4 was a moisture-activated self-adhering electrode. Electrode 22 was a water-coupled electrode designed specifically for use with the TENS device with which it was packaged. The remaining electrodes in this group used a synthetic polymer at the skin-electrode interface. No carbon-rubber electrodes were found in this group. Electrodes 2, 4, 7, 10, and 19 were designed for single use, whereas electrodes 5, 6, 11, 12, 18, 22, and 24 were of the reusable type. The two electrodes in the high-impedance group (electrodes 1 and 3) were of the pregelled, self-adhering type, both designed for single use.

Skin reactions were not seen with any of the electrodes, except for electrode 1. After both trials, a mild redness was noted beneath the proximal electrode. The redness involved the skin in contact with the adhesive but not that beneath the active part of the electrode. This hyperemic reaction resolved within 4 hours. No redness was observed beneath the distal electrode on the volar surface of the subject's wrist.

Discussion

The results of this study indicate that commercially available TENS electrodes vary in their conductive properties and that electrode selection affects impedance in this model system. Impedance, however, is determined by several elements in addition to electrodes and conducting medium. Interelectrode distance and differences in the thickness and texture of the skin each contribute to total impedance within the system. These variables were carefully controlled, however, by the use of a single subject and by the use of fixed electrode placement sites on the forearm. Differences in impedance attributable to normal anatomic variation were thus minimized or eliminated.

Impedance within the model system was determined by several factors, including the size of the conducting surface and the electrical properties of the conducting medium. Smaller electrodes will offer greater impedance than larger electrodes. We might expect, therefore, that the smaller electrodes in this study would be associated with higher impedance measurements than would electrodes with larger active areas. The electrodes in the high-impedance group were the smallest electrodes tested.

The electrical properties of the material from which the electrodes were constructed as well as the composition and distribution of the conducting medium may also have affected impedance. Several different gels and a variety of natural and synthetic poly-
meters served as conducting media in this study. All of the carbon-rubber electrodes using gel as a conducting medium were classified in the low-impedance group. This observation suggests that, as a group, standard carbon-rubber electrodes used with commercially available gels offer less impedance than electrodes used with other types of conducting media.24

We did not compare the size of the active area of individual electrodes with measured impedance values nor did we analyze the chemical composition of the various conducting substances. An analysis of the interaction among these factors was considered beyond the scope of this initial study. Our objective was rather to demonstrate that commercially available TENS electrodes vary in their conductive properties and can therefore affect the amount of stimulation delivered to the skin. It is not known whether the relative differences in conduction efficiency observed in this study correlate with any reported clinical benefits of TENS.4-6,10-12 Future work in this area might focus on determining which particular electrodes might be best suited for obtaining specific physiological or clinical results.

Skin Reactions

Several authors25-28 have reported skin reactions to either the stimulating current itself or to electrode adhesives and conducting gels. Reported reactions include mild inflammatory responses and small punctate burns in areas of high current density.21,25-28 Fisher and Brancaccio27 have shown that propylene glycol, which is a component of some electrode gels, may be irritating to the skin. We noted a skin reaction with only one of the electrodes tested. We attribute this response to some component of the adhesive to which the subject was sensitive. Because the observed skin reaction did not occur beneath the active part of the electrode, but rather involved the skin in contact with the adhesive, we feel confident that the impedance measurements obtained with these electrodes accurately reflect the impedance within the model system. We acknowledge, however, the need for a cautious interpretation of this conclusion.

Between-Trial Differences

Impedance differences were noted between trials with the same electrodes for all except three of the electrodes examined (Table). Several possible explanations for these differences might be advanced. Injury to the skin could have produced the observed differences. We think this explanation is unlikely in view of the fact that, with the exception of one electrode previously noted, no skin reactions were observed, and in that case the redness involved only the skin in contact with the adhesive. Moreover, at least 24 hours was allowed between each testing session. Microscopic injuries, not detectable by visual inspection, might have been produced and might account for the observed differences, but data to confirm or eliminate this hypothesis are not available.

Chemical reactions in the skin or involving the electrodes and conducting medium may also affect impedance within the model system. We think this explanation is also unlikely, because of the low levels of current used and the short length of time the current was applied. Rather we suspect that the measured between-trial differences reflect physical differences in the composition of the electrodes themselves in the case of the pregelled electrodes or those using natural or synthetic polymers or in the distribution of gel in the case of the carbon-rubber electrodes. Although these factors presumably did not affect the impedance measurements in this study, they may be of greater concern in other types of studies or clinical situations in which stimulation sessions are of considerably longer duration.

Our purpose in testing each electrode pair on two separate occasions was to ensure against technical failures involving the TENS device, battery, or lead wires that might have gone undetected had only a single measurement been taken. We were not attempting to assess the reliability of any particular electrode type. The fact that between-trial differences were found using a simple, standardized protocol that was rigorously followed suggests the possibility that different electrodes of the same type might not be identical in terms of their conductive properties. Future studies might focus on the question of electrode reliability and whether conductive differences among electrodes of the same type might be a source of variation in clinical response.

Clinical Implications

The results of this study suggest that TENS electrodes are different in terms of their conductive properties. The results do not address the issue of which electrodes can be regarded as poor, good, better, or best. The ability to make judgments of this type would necessitate the development of operational definitions of these terms and different experimental strategies and objectives that were not part of this initial study.

The clinical significance of the conductive differences reported in this article is unclear at present. Electrode-induced effects may be small with TENS devices that effectively maintain a constant current, more pronounced with TENS units that are less able to do so, and significant if constant-voltage TENS units are used.29-31 The observations reported in this article draw attention to electrodes and conducting media as potentially important variables in studies involving TENS. Additional research will be required to better understand how TENS affects nervous system function and in particular how this modality can be effectively used to reduce or eliminate pain. Further efforts in this regard might help explain some of the contradictory findings in the TENS literature and clarify a variety of clinically important issues.

Conclusions

The results of this study demonstrate that TENS electrodes vary in their
Appendix. Descriptive Characteristics of Individual Electrodes Used with Transcutaneous Electrical Nerve Stimulation Devices

1. Uni-Pulse® 600*: self-adhering, single use, pregelled, foam
2. Uni-Thin® 650*: self-adhering, single use, pregelled
3. Uni-Pulse® 685*: self-adhering, single use, pregelled, cloth
4. Tenzcare® 6221*: water activated, single use, conductive adhesive
5. Uni-Patch Multi-Day® 695*: self-adhering, reusable, synthetic polymer, foam
6. Uni-Patch Encore® 693*: self-adhering, reusable, PolyHesive® gel
7. SUE®*: self-adhering, single use, karaya with foam backing
8. Staoderm III**: self-adhering, single use, pregelled
9. Medtronic Model 3796**: reusable, carbon-rubber, chloride-free Neuromod® gel
10. Comfort Ease® 7791**: self-adhering, single use, synthetic polymer
11. Neuroaid® 3798**: self-adhering, reusable, synthetic polymer
12. Neuroaid® 3799 (HH)**: self-adhering, reusable, hydrophilic synthetic polymer
13. EMPI Model 94050**: reusable, carbon-rubber, chloride-free gel
14. Dermapad™**: self-adhering, reusable, karaya with carbon-rubber backing
15. Tenzcare® 6221*: self-adhering, reusable, water activated, conductive adhesive
16. WITPAD**: self-adhering, reusable, karaya with carbon-rubber backing
17. Carbon-rubber**: reusable, salt-free Uni-Pulse®
18. PALS® 86100**: self-adhering, reusable, PolyHesive® gel
19. Protector® 142-KC**: self-adhering, single use, polymer, cloth
20. Carbon-rubber**: reusable, salt-free Spectra® 360 gel
21. Carbon-rubber**: reusable, chloride-free conductive gel
22. Sponge Electrode**: reusable, water-conducting medium
23. Bioform™**: reusable, carbon-rubber, chloride-free Biogel™
24. Sentry Silver Circuit Dura Durr® 5001**: self-adhering, reusable, synthetic polymer
25. Carbon-rubber**: reusable, chloride-free Lectron 111™ gel

*Uni-Patch Inc, 1313 Grand Blvd W, PO Box 271, Wabasha, MN 55981.
13M Medical-Surgical Div, Bldg 225-SS, 3M Center, St Paul, MN 55144-1000.
3Valleylab Inc, Boulder, CO 80301.
4EMPI Inc, Fridley, MN 55432.
5Stoedtner Inc, 1225 Florida Ave, PO Box 1379, Longmont, CO 80502-1379.
6Medtronic Inc, Neuro Div, 7000 Central Ave NE, Minneapolis, MN 55432.
7Codman & Shurtleff Inc, Randolph, MA 02368.
8Waltham International Trade Inc, Roselle, NJ 07203.
9Avedaard Manufacturing Co Ltd, Huntington Beach, CA 92646.

**Medical Designs Inc, 929 Eastwind Dr, Ste 201, Westerville, OH 43081.
3Parker Laboratories Inc, 307 Washington St, Orange, NJ 07050.
**NTRON Electronics Inc, PO Box 7000, San Rafael, CA 94901.
***Medical Adhesives Inc, Columbus, OH 43215.
*Medical Laboratories Inc, Elmwood Park, NJ 07407.
**Biostem Inc, Princeton, NJ 08540.
3Sentry Medical Products Inc, Santa Ana, CA 92707.
3Tens X Tec, Orlando, FL 32804.
***Pharmaceutical Innovations Inc, 897 Frelinghuysen Ave, Newark, NJ 07114.

Conductive properties. Thus, like amplitude, pulse duration, and frequency, electrodes and conducting media represent variables that may affect the pain-relieving effects of TENS. These observations emphasize the need to include information about electrodes in reports concerning TENS and call attention to the importance of controlling for this source of variability in future clinical and basic science studies.

References


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