**SURFACE ELECTROSTIMULATION ELECTRODES**

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1. INTRODUCTION

When a stimulating current is applied to the electrodes placed on the skin overlaying sensory-motor structures, an electric field is established between two electrodes (Fig. 1) and ions will create a current in the tissues. The ionic flow across the nerve influences the transmembrane potential and can generate an action potential. The action potential propagates along the nerve causing either contraction of a muscle in the case of motor nerve stimulation or blocking of the pain transmission when stimulating peripheral sensory nerves in the skin.

Surface stimulation electrodes are predominantly used for training of disuse atrophied muscles in lower or upper extremities of patients with lesions of the central nervous system (1-4). Such electrical stimulation exercise results in cyclical movements of selected limb segments. The usual frequency of electrical stimuli is between 20 Hz and 50 Hz, and pulse duration is between 0.1 ms and 0.3 ms. The intensity of the electrical pulses can go up to 100 mA in the case of a constant current stimulator or can exceed 100 V when using a constant voltage output. Cyclic trains of electrical stimuli are also used in strengthening of muscles in sports and fitness centers. To a lesser extent, surface stimulation electrodes are used in gait training after stroke or incomplete spinal cord injury (5). Important use of surface electrodes is encountered in peripheral neuromodulation of pain (6). Here pulse durations between 0.05 ms and 0.15 ms, frequencies from 40 Hz to 150 Hz, and amplitudes up to 50 mA are applied. Transcutaneous electrical stimulation was found helpful when treating peripheral nerve injury pain, low back pain, postoperative pain, and pain caused by vascular diseases.

The surface stimulation electrode is a terminal through which electrical current passes into the underlying tissue. At the electrode–tissue interface, a conversion occurs between the current of electrons driven through the wires coupled to the stimulator and the current of ions in the tissue. An electrode is usually made of metal. However, it may be made of a nonmetal, commonly carbon. The electrode through which current passes from the metallic or nonmetallic conductor to the tissue is called the anode and that through which current passes from the tissue to the conductor is the cathode. In electrical circuits, the current flows from the terminal at higher electrical potential to the terminal at lower electrical potential. In this way, the anode is the positive electrode and the cathode is the negative electrode.

Besides distinguishing between positive and negative electrode, we also discuss the unipolar and bipolar electrical stimulation technique. With unipolar stimulation, one electrode is often considerably smaller than the other, whereas the electrodes used in bipolar stimulation both have the same size. In unipolar stimulation, the smaller electrode is negative and is called an active electrode because in its vicinity, depolarization of the membrane of nerve fibers occurs. In motor nerve stimulation, the active electrode is positioned as closely to the motor point of the muscle as possible. Motor point is a site on the skin, where the amplitude of the stimulus required to fully activate the muscle is at a minimum. This is a site where all motor nerve fibers are closest to the stimulating electrode. In multichannel electrical stimulation systems, it is possible to have a single anode and several independent cathodes or to have separate anodes and cathodes that are galvanically separated.

Two important mechanisms that help to transfer the electron conduction in the solid state into an ion conduction in the electrolyte are capacitive and electrochemical. The capacitive mechanism is represented by the transport of electrons to the metal surface and the transport of ions to the electrode surface. Electrochemical mechanism refers to corrosion of the electrodes and the electrolysis of water. Chemical reversibility occurs when all processes occurring at the electrode after the application of a current pulse are reversed by a second current pulse of the opposite polarity (7). The least damaging waveforms are charge-balanced biphasic currents with no net dc component. In surface electrical stimulation biphasic stimuli result in less pain sensation and skin irritation. Also, in the case of biphasic currents we can no more speak about one electrode as anode and another as cathode.

Let us examine four properties of surface stimulation electrodes and electrodes positioning, exerting an essential influence upon the effectiveness of electrical stimulation: electrode size, polarity of electrodes, resistance, and distance between the electrodes. Electrical stimulation is applied on a nerve fiber, since muscle fibers have a considerably higher stimulation threshold. Thus we can say that larger electrodes are used to stimulate the nerve endings spreading all over the underlying tissue, whereas smaller electrodes are applied to influence the nerve when the latter comes closer to the skin. By larger electrodes, stronger contraction is obtained along with a reduced current density and a likewise less pronounced unpleasant sensation on the skin. However, large electrodes permit no selective choice of a desired movement of the stimulated paralyzed extremity. The active areas of electrodes range between 2 cm² and 50 cm². Electrodes of 2 cm² to 4 cm² are used to stimulate the nerves near the surface, and those of about 8 cm² for the stimulation of smaller muscles, whereas electrodes of 25 cm² or more are used in case of larger muscles or dermatomes. A positive and a negative electrode are placed along the muscle to be stimulated. Considering their polarity, the electrodes are positioned to provoke an optimal movement from the functional point of view. Stronger movement is usually obtained by placing the positive electrode distally.

Another important property of electrical stimulation is the impedance between the electrode and the skin. It is desirable that the resistance should be as low as possible to avoid energy losses before the stimulation has reached the neuromuscular tissue. The electrode impedance is frequency dependent. The dc (or low-frequency) impedance tends to be several orders of magnitude larger than the
impedance at higher frequencies. Nominal values of 2 kΩ are encountered (8). The contact conduction is increased by moistening the electrodes with water or special conductive electrode gels. A high resistance to electrical currents is offered by adipose tissue. To attain the muscle through this tissue, higher stimulation amplitudes should be used, causing a feeling of pain in the skin. Bones are also very bad conductors of electric current; electrical stimulation cannot reach the muscles that are behind them.

An important parameter in positioning of stimulation electrodes is also the distance between the electrodes. Figure 1 shows an electric field between a positive and a negative stimulation electrode on the assumption that the tissue is homogeneous. The greatest current density appears at the skin–electrode contact and tends to decrease with distance from the electrodes as the flow spreads out over a larger area. Closely spaced, small electrodes generally make the effective area of stimulation rather superficial due to the lower impedance of the current path through proximal tissue. The deeper tissue will be attained by a greater distance between the electrodes. Increasing the electrode separation leads in general to an increase of the maximal achievable force. If the skin between the electrodes is too moist, this causes the current between the electrodes to flow to the skin, which results in a burning sensation and slight or no muscle contraction at all.

2. THEORY

The task of transcutaneous electrical stimulation is to overcome the impedance of the skin to activate the motor or sensory nerves underlying the surface. The surface electrodes problem can be presented by an equivalent circuit of the electrodes and its interface with the body (Fig. 2). The resistor $R_s$ models both the resistance of the skin and the deep tissues. The parallel combination of capacitor $C_p$ and nonlinear resistor $R_p$ is intended to model the skin impedance. Skin, namely, exhibits different amplitude and frequency-dependent nonlinear effects. A series capacitance $C_{pol}$ and resistance $R_{pol}$ model the electrode–skin interface (9).

It was demonstrated that for square stimulation pulses, the capacitance $C_{pol}$ is negligible, so that the polarization impedance of the electrode–electrolyte interface could be equated to a pure resistance $R_{pol}$. Resistance $R_p$ is localized exclusively in the stratum corneum and varies markedly with the current intensity, the intensity of a previous pulse, and the interval between the pulses (10). The resistance $R_s$ has two components. The first one, which varies with intensity of stimuli, is localized in the stratum corneum. The second one is constant with intensity of stimulating pulses and is found in the subcutaneous tissues. Removal of the stratum corneum is shown to reduce the value of $R_s$ while almost eliminating $R_p$ with its appertaining nonlinearities. The ionic conduction within the stratum corneum seems to be the main cause of the intact skin nonlinear impedance properties.

The most important stimulation parameter is electrical current through the tissue to be stimulated. The current intensity of constant voltage stimuli, applied to the intact skin, cannot be adequately controlled because of the mentioned variations of $R_p$. The current intensity of transcutaneous electrical stimulation can only be controlled satisfactorily when constant current stimuli are used.

3. EQUIPMENT

The design criteria for surface stimulation electrodes are as follows: physical comfort to the skin, electrical surface area greater than 4 cm² preventing skin irritation, use of hypo-allergenic materials, flexibility to follow body surface, ease of attachment, ability to remain in position for the duration of at least one active day, reusable, low cost, reliable means of connection to stimulator, resistant to medical solvents and electrode gels, and low and stable electrical resistance.

The simplest among the surface electrodes consists of a metal plate or metal wire mesh coated with fabric or sponge. Common materials used are stainless steel, silver–silver chloride, platinum, or gold. For purposes of

Figure 1. Electric field between a positive and negative electrode.

Figure 2. An equivalent electrical model for skin and deep tissue.
Identifying optimal placement of a surface electrode is a time-consuming process. The problem can be overcome by the use of transcutaneous electrode arrays. Here, the desired location of the electrode is electronically selected. The stimulation electrode is a two-dimensional array of small (1 cm²) elements. Two types of such matrix electrodes were presented at the 2004 Vienna Workshop on FES (Functional Electrical Stimulation) (12,13). They consist of either 16 or 24 electrode elements. The elements can be independently switched on or off, and in this way, the most adequate size, shape, and position of the electrode is obtained without moving the electrode. Such a reconfigurable surface electrode enables improved selectivity of muscle activation. Also, the stimulation pattern can be changed during movement of the limb, as the electrode moves with respect to the nerve. Another advantage of an array of surface electrodes may be the reducing of stimulated muscle fatigue. In a four-electrode array, only one pair of electrodes was activated at any given time (14). In this way, only one part of the muscle exceeded the activation threshold, whereas the other part remained at rest, reducing fatigue of the entire muscle.

A matrix of electrodes (1 mm to 3 mm in diameter) transducing small electric currents (1 mA to 7 mA) into the skin can be used in so-called electrotactile or electrocutaneous stimulation. The benefit of an electrotactile display is the dynamic capability of presenting different patterns over a short period of time. Electrocutaneous stimulation presents sensory substitution for blind or deaf persons and for users of prostheses. Electrotactile stimulation may also be used in virtual reality, telerobotics, and telepresence. The electrotactile pattern can be displayed to various cutaneous loci, such as the fingertips or abdomen (15,16).

4. EVALUATION

Let us mention the problems common to more or less all surface stimulation electrodes. In case of improper handling, electrodes can damage the skin in the contact area. Here it must be mentioned that burns typically occur under the anode but not the cathode when using identical surface electrodes (17). Another problem resides in a precise electrodes positioning along a muscle. Sometimes a mere displacement of an electrode for just a few millimeters completely changes the muscle response. This happens when a selected nerve (e.g., peroneal nerve) should be stimulated by surface electrodes. Another inconvenience related to the surface electrodes is that they excite pain receptors in the skin. Fortunately often, the patient’s sensitivity is considerably reduced, or sometimes it is lost to such an extent that the sensation of pain is not critical. Another problem is undesired motion of the skin with respect to the neuromuscular tissue. Even though an electrode seemingly occupies the same place all the time, its distance from the nerve is not constant. This is one reason why the movements caused by electrical stimulation cannot be easily repeated. Another limitation encountered with surface electrodes is that small muscles generally cannot be selectively activated and deep muscles cannot

Figure 3. A perspective view of the stimulation electrode with a portion of a nonconductive sheet thereof peeled back.
be stimulated without first exciting the superficial muscles. Relatively high voltages, sometimes in excess of 100 V, between electrode pairs may represent a certain hazard for the patients and the personnel that treat them. Finally, the applicability of the surface stimulation electrodes depends on the fixation problems. Stretchable garments with electrodes already mounted in appropriate locations have been developed by several manufacturers to simplify the application of electrodes to the skin surface. In the case of lower limb stimulation, the fixation problems can be overcome by specially designed trousers carrying stimulation electrodes and cables (18). Such stimulation equipment is comfortable and easy to handle and was tested even under the space conditions. A very aesthetic and practical solution was used in the noninvasive upper limb neuroprosthesis (19). Here, the surface stimulation electrodes were built into an elegant, self-aligning, and flexible splint. The splint provides additional fixation of the wrist joint and allows the entire electrode array to be positioned within a few seconds.

Different types of surface stimulation electrodes were evaluated for their effectiveness. At Rancho Los Amigos Hospital, self-adhering disposable pregelled pads, carbon-loaded conductive silicon rubber electrodes, and felt-covered metal plates were tested (20). Stimulation with felt pads produced a mean maximum torque that was 72% of the maximum voluntary knee extensors torque. Conductive rubber produced 62% and pregelled electrodes 37% of the maximal voluntary torque. Interesting to note is that felt pads soaked with either tap water or saline solution provided the highest mean comfortable torque and the lowest impedance. The first two types of electrodes were also evaluated over a period of 5 consecutive days. The electrodes were left in place after each test session. Pregelled electrodes produced the most skin reactions, whereas carbon rubber electrodes produced only mild skin reactions.

The influence of surface electrodes positioning on the recruitment curve assessed in ankle plantarflexors was studied in healthy and paraplegic persons (21). Here, the nonlinear recruitment curve described the dependence of isometric ankle joint torque on the duration of stimulation pulses. Three different trials were performed: (1) The electrodes were kept on the skin without taking them off for 5 days, (2) the same electrodes were applied every day on the same marked area on the calf, and (3) the same set of electrodes was applied for 5 days approximately on the same unmarked area. Self-adhesive Aaxelgard’s 50 mm diameter electrodes were placed on the midlines of the soleus and gastrocnemius muscles. Good agreement between curves was measured in first two trials, suggesting that nonlinear recruitment does not change if surface electrodes are kept on the skin for several days or if electrodes are applied on the same marked area repeatedly. Significant discrepancies appeared in the third trial where the electrodes were placed on the same unmarked area every day.

In another study, the effect of electrode size, shape, and placement were studied to assess what current is required to reach a set muscle force (22). The electrodes were placed at different distances from the motor point. The associated subject’s comfort was recorded on a visual analoge pain scale. Placement of the electrode off the motor point during the application of electrical stimulation caused a significant increase in the amount of current required to achieve a set muscle force, with a concurrent increase in the subject’s discomfort. Small differences in size and shape of clinically available electrodes do not seem to affect the patient’s tolerance to electrical stimulation.

Not all processes at the surface electrodes are completely understood or entirely investigated. Due to high skin impedance, the energy required with surface stimulation is much higher than with stimulation electrodes placed on the surface of the muscle, in the muscle, on the motor nerve, or in the nerve. It is also not difficult to realize that most of the inconveniences of the surface stimulation electrodes enumerated in this article can be overcome by the use of implanted electrodes. Nevertheless, because of their simple noninvasive application, the surface electrodes will remain to be used in future therapeutic treatments.

**BIBLIOGRAPHY**


