VOLTAGE-CURRENT CHARACTERISTICS OF THE ELECTROTACTILE SKIN-ELECTRODE INTERFACE

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ABSTRACT

During electric stimulation of the sense of touch the static skin-electrode resistance decreases nonlinearly with increasing stimulation current. We present a mathematical model which fits these data and has a possible physical explanation. We also model the voltage vs. time response of an electrode stimulated with constant-current pulses. We provide two possible explanations for this characteristic.

INTRODUCTION

Localized tactile sensations ranging from tingle to vibration to stinging are produced when pulses of current (10-500 µs, 1-20 mA, 1-100 Hz) are passed into the skin through 1-10-mm skin electrodes. Szeto and Saunders [1] review applications of electrotactile stimulation including sensory prostheses for the deaf and blind.

We can use the electrical properties of stimulated electrodes to design a practical stimulator circuit and to provide insight into the nature of the skin-electrode interface. We have used pulsatile stimulation because sinusoidal excitation obscures the fundamental nonlinearities of the skin-electrode interface. The term "impedance" is therefore only properly used to describe the small-signal (e.g. biopotential recording) properties of the nonlinear skin-electrode system.

We used balanced biphasic current waveforms (zero net dc current) but show data only for the positive phase. The negative phase gives similar results.

The electrodes used are those of the Tacticon (Concord, CA) model 1600 auditory prosthesis. Sixteen 5.5-mm gold-plated electrodes are mounted on a belt which encircles the abdomen. All of the electrodes share a common reference plane which is the conductive rubber base material of the belt. The skin and belt were moistened with tap water before the experiment to facilitate proper electrical contact [1].

STATIC V-I CHARACTERISTIC AND MODEL

Figure 1 shows the voltage recorded across an electrode stimulated with 1-mA, 400-µs pulses at a rate of 10 pulses/s. Consider now only the steady-state electrode voltage V_m near the end of the current pulse. Figure 2 shows that this voltage increases nonlinearly with stimulation current. Figure 3 shows the same data plotted as static resistance ($R = V_m/I$) vs. current.

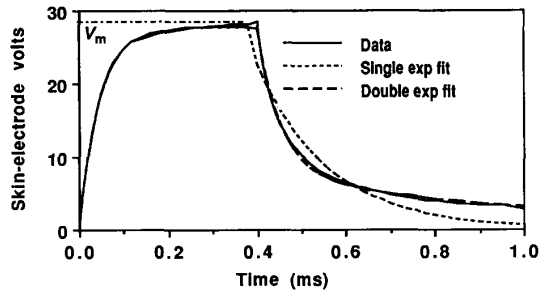

Fig. 1. Electrode voltage from a 400-µs 1-mA current pulse; two exponential models.

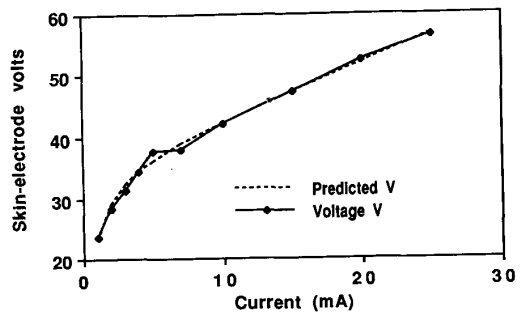

Fig. 2. Voltage across the skin-electrode interface as a function of stimulation current.

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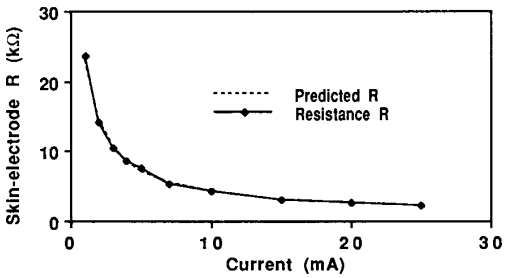

Fig. 3. Resistance of skin-electrode interface as a function of stimulation current.

A mathematical model which fits the data in Figs. 2 and 3 is

$$R(i) = R_0 + RpRv(i)/(Rp + Rv(i)) \quad (1)$$

$$Rv(i) = RpI_0/i \quad (2)$$

where R_0, R_p, and I_0 are empirically-determined constants. Figure 4(a) shows a simple physical realization of (1) and (2). The exact correspondence (if any) of the elements of Fig. 4(a) to the skin-electrode interface is not known. Szeto and Saunders [1] and Grimnes [2] propose that the sweat ducts carry most of the current across the skin, so the current density in these ducts may be high enough to heat the sweat. However, the conductance of 0.017-0.051 mM NaCl solution (the approximate ionic content of sweat) only increases 100% from 40°C to 100°C. Therefore, heating of sweat in the sweat ducts cannot account for the 30-fold change in R(i). Grimnes [3] discusses other possible mechanisms including electrically-driven filling of sweat ducts.

A least-squares nonlinear regression using the SYSTAT software package determined the following values for the constants in (1) and (2) using the data in Fig. 2: $R_0 = 0.895$ kΩ, $R_P = 60.1$ kΩ and $I_0 = 0.585$ mA.

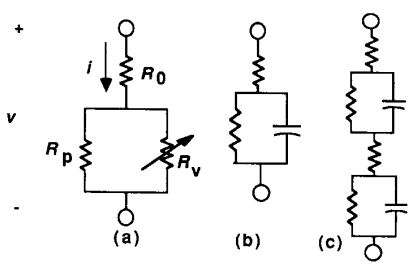

Fig. 4. Electrode-skin models.
(a) Nonlinear static resistance model.
(b) Single exponential dynamic model.
(c) Double exponential dynamic model.

DYNAMIC VOLTAGE CHARACTERISTIC WITH CONSTANT CURRENT STIMULATION

A casual glance at Fig. 1 suggests that the voltage response to a constant current pulse is a simple exponential rise and fall modeled by the classical electrode model Fig. 4(b). The Fig. 4(b) skin-electrode voltage is:

$$\text{Rise: } v(t) = V_m(1 - e^{-t/\tau}) \quad (3)$$

$$\text{Fall: } v(t) = V_m e^{-t/\tau} \quad (4)$$

where $\tau = RC$ and $V_m = IR$. Note that t in the fall phase is normalized so that t = 0 corresponds to the end of the current pulse. We also ignore the series resistor in Fig. 4(b); it's value of 200-900 Ω is small compared to the total electrode resistance. It likely represents the electrolyte-electrode resistance. We measured a resistance of 565-625 Ω for the electrode applied to a saline-soaked (34 mM) paper towel at currents of 0.1, 1, and 10 mA.

Figure 1 shows the voltage predicted by (3) and (4) where V_m and τ are chosen for a least-squares fit. ($V_m = 27.7$ v and $\tau = 46.7$ μs.) While the rise phase is modeled quite well by (3), the fall phase is not modeled by (4). Not only are the model parameters changing between the rise and fall phases, but the model itself is changing or is inadequate.

Since the skin is a multilayer structure, we might assume the double exponential model in Fig. 4(c), which is described by:

$$\text{Rise: } v(t) = V_{m1}(1 - e^{-t/\tau_1}) + V_{m2}(1 - e^{-t/\tau_2}) \quad (5)$$

$$\text{Fall: } v(t) = V_{m1}e^{-t/\tau_1} + V_{m2}e^{-t/\tau_2} \quad (6)$$

We were not able to find parameters for (5) using the data in Fig. 1; V_{m1} and τ_1 tended toward V_m and τ in the simple model (1) and τ_2 tended to infinity. We conclude that for the rise phase, a double exponential model is not necessary. However, Fig. 1 shows that (6) models the falling phase much better than (4). ($V_{m1} = 19.6$ v, $V_{m2} = 7.8$ v, $\tau_1 = 52.8$ μs and $\tau_2 = 642.6$ μs.

Using two different models for rise and fall seems unphysiological. It is likely that a better model might have time-varying parameters.

REFERENCES

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