PERIODIC VARIATIONS IN THE ELECTROTACTILE SENSATION THRESHOLD

Kurt A. Kaczmarek, John G. Webster, and *Robert G. Radwin

Department of Electrical and Computer Engineering
*Department of Industrial Engineering
University of Wisconsin
Madison, WI 53706

ABSTRACT

The sensation threshold current for electrotactile (electrocutaneous) stimulation increases and decreases over time with a period of 3–10 min. The magnitude of these variations ranges from unmeasurably small to 25% of the average sensation threshold. The thresholds of two electrodes separated on the skin by 11 cm are loosely correlated in time. These periodic variations do not appear to be related to changes in the static electrode–skin resistance, to respiration, or to the periodic sampling process used in measurement.

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 diameter skin electrodes. Electrotactile stimulation may be useful for tactile displays as part of sensory prostheses for the deaf and blind [1], [2].

It has long been known that the sensation threshold, strength, and "quality" of electrotactile stimulation vary with the stimulation waveform, and with the location, size, and geometry of the electrode on the skin. However, we do not believe that periodic time variations have been previously reported, perhaps because they have been dismissed as random noise.

MATERIALS

An automated electrotactile stimulation system (ETSS) provides stimuli and response logging for all experiments. A custom waveform generation (WG) circuit controlled by an IBM PC produces balanced-biphasic pulses (100-μs positive phase, 100-μs interphase interval, 100-μs negative phase) at a repetition rate of 10 Hz.

A custom voltage-to-current converter (VIC) circuit converts the voltage waveforms from the WG into current waveforms for the stimulation electrodes. The VIC has an maximal voltage compliance of 100 V and an output resistance of 2–5 MΩ so that the stimulation current is independent of electrode impedance over the expected range of approximately 1–25 kΩ [3]. The pulse rise and fall times are less than 1 μs.

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 are moistened with tap water before the experiment to facilitate proper electrical contact [2]. The belt is mounted 15 min before the experiment.

For the few experiments using vibrotactile (vibrating) simulation, 600-μs current pulses drive miniature audio transducers (Star Micronics QMB-105) at a pulse repetition rate of 10 Hz. Because these transducers are highly nonlinear, the mechanical waveform at the abdominal skin is unknown. White noise from headphones worn by the subject masks the noise from the transducers to prevent aural cues.

A potentiometer connected to the PC via an analog-to-digital converter allows the subject to control the stimulation current (or vibration amplitude) when prompted. The PC records stimulation current with an accuracy of ±5% and a linearity of ±2% over the ETSS operating range 1–40 mA.

To prevent the subject from using potentiometer position as a cue for determining sensation thresholds, the relationship between potentiometer rotation and stimulation current is different for each experimental trial. The function is

$$i = 7.5(x - \mathrm{RND}/2) \quad \text{subject to} \quad i \geq 0$$

where i is the stimulation current in mA; x is the potentiometer position and 0 is fully counter-clockwise (CCW) and 1 is fully clockwise (CW); and RND is a random number between 0 and 1.

METHODS

Every 15 or 30 s as requested, the subject sequentially determined the sensation threshold for two electrodes "A" and "B" separated by 11 cm on the electrode belt (5 electrodes in from the left and right ends of the belt, respectively).

A modified method of limits provided rapid determination of the sensation thresholds (15 s for both determinations). At the appropriate instant, we instructed the subject to turn the potentiometer CW from zero until he could just feel the stimulus. Frequently, the subject would overshoot the threshold position because of the randomization function. The subject then readjusted the knob CCW (and CW again if required) until the stimulus was just perceptible. The subject always determined how many such readjustments were required to find the threshold before entering the response by pressing a button. With 5 min of practice this tweaking process became second-nature.

Approximately 32 min of data collection provided either 128 or 64 threshold determinations for each electrode, depending on whether the sampling interval was 15 s or 30 s. The sequential nature of the threshold determinations causes the electrode B data to be approximately 10 s behind electrode A data (not shown on graphs).

All of the data in the graphs were collected with the first author as the (best-trained) subject. Data from two other subjects show a bit more scatter, but otherwise similar results. All three subjects were 25–30-year old male university graduate students.

RESULTS AND DISCUSSION

Figure 1 shows a typical plot of the electrotactile sensation threshold vs. time for the 32-min experiment with a 30-s sampling interval. The cyclical nature of the sensation thresholds is evident above the scatter, but the period repetition and general shape of the data over time are not clear. In this plot, for example, the period for electrode B seems to change from 9 min to 4 min over the course of the experiment. Replications of this experiment showed more and less data scatter and more and less uniformity of the cyclical variations. In some cases, the variations seem entirely random. In other cases, the peak-to-peak amplitude of the fluctuations was as much as 25% of the average threshold.

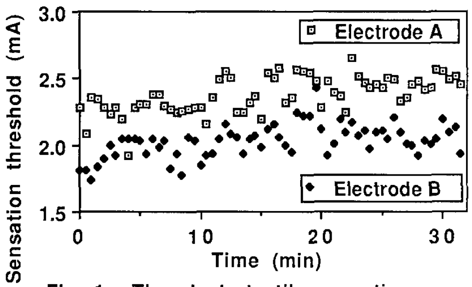

Fig. 1. The electrotactile sensation threshold varies periodically with time.

To illustrate whether the sensation thresholds for the two electrodes are correlated in time, Fig. 2 shows a scatterplot of the same data as in Fig. 1. A positive correlation is evident from visual inspection; the correlation coefficient r = 0.52. Three replications of this experiment showed less correlation: 0.22, 0.28, and 0.28. All, however, were positive, indicating that there is likely some common mechanism affecting the sensation threshold at both skin sites. This mechanism may or may not be the same one responsible for the periodicity.

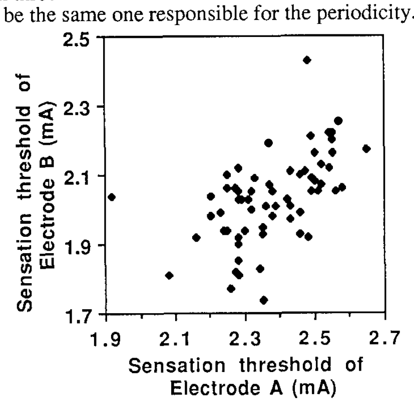

Fig. 2. The electrotactile sensation thresholds of two electrodes are loosely correlated in time.

We chose 64 and 128-point samples so that a fast-Fourier transform (FFT) could provide frequency domain information not visible in the time plots. However, the power spectra of most of the data were too noisy to identify frequency peaks relating to periodic behavior. To improve the signal-to-noise ratio in this analysis, we averaged the power spectra for 4 replications of the above experiment (a total of 8 spectra, because each experiment produces two time series). Figure 3 shows that a clear peak of periodic activity occurs at 0.16 cycles/min, or a period of 6.4 min.

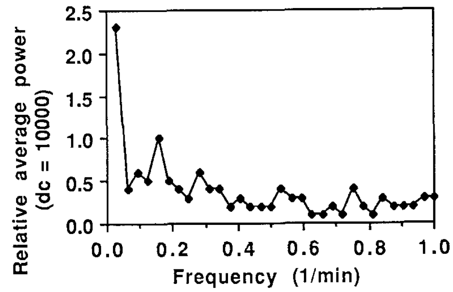

Fig. 3. The average power spectrum of the sensation threshold for 8 electrodes shows a peak at a period of 1 cycle/6.4 min.

Visual inspection of time plots of these and other similar experiments reveals periods of 3–10 min. Note the vertical axis scaling; the dc component is at 10000, well off the scale. The low-frequency peak at 0.031 cycles/min (32-min period) represents the slow upward drift of sensation thresholds during the experiments. This drift was not always evident and not always positive.

Other experiments attempt ed to determine the source of the periodic threshold variations. A 15-s sampling period showed similar results to a 30-s period, indicating that 30 s is not special in any way. Further proof of this was provided by an experiment with random sampling times; the period between samples varied randomly from 10 s – 60 s. This method of data collection did not eliminate the periodicity.

To determine if respiration (which causes mechanical stretch on abdominal skin) could be involved, we had the subject determine sensation thresholds only at peak expiration in quiet tidal breathing, with the breath gently held during the threshold determination. No differences were apparent between these data and data taken with normal breathing.

We found that the periodic activity occurred for electrotactile stimulation on the thigh as well as the abdomen, ruling out the possible influence of gastric and intestinal smooth muscle activity.

Because the static resistance [3] of the electrode-skin interface did not change during a 30-min period with periodic application of a 1-mA test stimulus, changes in the electrode-skin interface are not likely responsible for the periodicity.

Finally, the sensation threshold for vibrotactile stimulation on the abdomen showed similar periodic behavior, further suggesting that the mechanism is not related to the electrical properties of the electrode-skin interface.

REFERENCES

[1] K. A. Kaczmarek, J. G. Webster, P. Bach-y-Rita and W. J. Tompkins, "Electrotactile and vibrotactile displays for sensory substitution," *IEEE Trans. Biomed. Eng.*, 1990 (in press).

[2] A. Y. J. Szeto and F. Saunders, "Electrocutaneous stimulation for sensory communication in rehabilitation engineering," *IEEE Trans. Biomed. Eng.*, vol. BME-29, pp. 300–308, 1982.

[3] K. A. Kaczmarek, "Voltage-current characteristics of the electrotactile skin-electrode interface," *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, vol. 11, pp. 1526–1527, 1989.

This work was supported by NIH grant NS26328.

Telephone 608-263-1572.