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Original article

Cutaneous perception of electrical direct current

Ørjan G. Martinsen [a,*], Sverre Grimnes [a,b], Hossein Piltan [a]

[a] Department of Physics, University of Oslo, PO Box 1048, Blindern, 0316 Oslo, Norway
[b] Department of Clinical and Biomedical Engineering, Rikshospitalet, 0027 Oslo, Norway

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Abstract

We have investigated the threshold level of perception for dc current in human skin in order to determine whether it is best described as a function of current or current density. The threshold was found to be more dependent on current than current density, and a spatial summation effect in the nervous system is suggested as one possible cause of this finding. The perception typically persisted for a long time after the current had been switched off, indicating that the nerves are excited by chemical products of the dc current and not by the current itself.

Résumé

Nous avons étudié le niveau de seuil de la perception du courant continu dans la peau humaine afin de déterminer si cette perception est mieux fonction de la densité ou l'intensité du courant. Le seuil s'est avéré plus dépendant de l'intensité que la densité, et une cause possible en est l'effet spatial additif dans le système nerveux. Typiquement, la perception persiste pendant longtemps après que le courant ait été coupé, indiquant que les terminaisons nerveuses sont excitées par les changements biochimiques induits par le courant continu et non par le courant lui-même.

Keywords: Perception; Skin; Electric direct current; Spatial summation

Mots clés : Perception ; Peau ; Courant continu ; Addition spatiale

1. Introduction

Perception of ac and dc currents is caused by quite different mechanisms. Ac excites nerves directly or indirectly [1], and as soon as the current is switched off, the perception disappears. Apart from very low frequencies, this mechanism can be considered linear with potential levels proportional to the applied current.

When a dc current is slowly increased to a constant low level, there is initially no perception. After some time, in the order of seconds or minutes, the perception slowly appears. The sensation is quite difficult to detect, and therefore also the time of the start of sensation.

Forbes and Bernstein [2] investigated the significance of contact area on the threshold of perception of 60 Hz current on the palmar side of the middle finger. They used two equally sized electrodes and gradually increased the current level until the test subject reported that stimulation was felt. They found that the total current necessary for threshold stimulation increased logarithmically with electrode area, and that the necessary current density decreased with area.

Dalziel and Mansfield [3] found a mean threshold level of perception of 5 mA dc, compared to 1 mA, 60 Hz current. He used bipolar smooth nr. 7 copper wire electrodes held in each hand. He also found the threshold of perception of 45 μA for both dc and 60 Hz current at the tongue. He used bipolar platinum nr. 18 wire electrodes, each 1 in. long. Dalziel and Mansfield [3] examined the effect of contact area, but found only a small correlation with the threshold level.

Prausnitz [4] reviews a number of investigators related to transdermal iontophoresis and finds from a power function least-squares fit of the total data, the following electrode area

* Corresponding author. Tel.: +47-22-85-6474; fax: +47-22-85-6422.
E-mail address: ogm@fys.uio.no (Ø.G. Martinsen).

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dependence for the perception thresholds of current I and current density J (S is area in cm^2):

$$I_{th}\ [\text{mA}] = 0.42 \cdot S^{0.21}\ (R^2 = 0.47)$$
$$J_{th}\ [\text{mA/cm}^2] = 0.42 \cdot S^{-0.79}\ (R^2 = 0.93)$$

Using µA and mm instead, gives:

$$I_{th}\ [\mu\text{A}] = 160 \cdot S^{0.21}$$
$$J_{th}\ [\mu\text{A/mm}^2] = 160 \cdot S^{-0.79}$$

where S now is in mm^2.

The shape or frequency of the current waveform used are not taken into account here, however, and Prausnitz writes that different waveforms commonly used for stimulation in commercial instruments, give with a reasonable approximation the same stimulation.

Since perception of dc current is different from ac current or pulsed dc current, we wanted to study the relationship between perception threshold for dc current and electrode area in order to reveal whether the threshold is best described by current or current density. The dependence was examined with dry plate electrodes of different contact areas.

2. Materials and methods

Dry metal plate electrodes with areas in the range 1–100 mm^2 were produced in mild steel, gold, silver, platinum and titanium. They were positioned directly on the palmar side of the distal phalanx of the middle finger at a controlled and constant pressure of 15 kPa. Other skin sites like ventral side of wrist and palmar sites were also tested. All measurements were performed at room temperature on both hands of two healthy, trained, male volunteers.

The electrodes were used in a monopolar system with an 81 cm^2 Europlate® reference electrode at the same ventral forearm. Preliminary tests showed that a reference electrode area larger than 10 cm^2 was necessary to assure that the first sensation appears at the working electrode. These tests also showed that if the working electrodes were applied to the skin for more than about 3 min, this could produce a mechanical stimulation of the skin that could be mistaken as an electrical stimulation.

The following procedure was therefore chosen: The current was initially adjusted to a preset level with positive polarity at the working electrode, assumed to be too small to give a perception response within 3 min. If no electrical perception occurred during the first 3 min, a higher current level was tested 2 h later on the same site, and this process continued in steps of 10 µA until the dc was perceived. It was hence assumed that any electrically induced biochemical changes in the skin were reverted within 2 h. The current level was always chosen small enough to avoid ac current sensation at the moment of electrode onset. We also carried out some measurements with negative polarity at the active electrode, but the results were difficult to reproduce and hence discarded. The reason for this is probably electro-osmosis in the sweat ducts, a mechanism that actively fills the ducts with moisture and hence produces high local current densities [5].

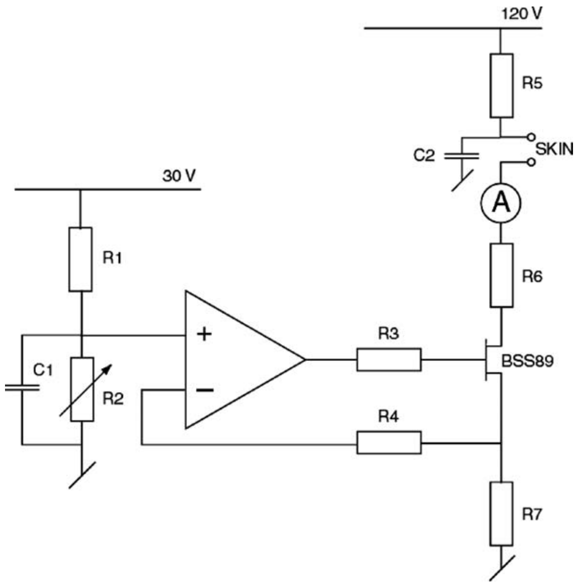

Fig. 1. Electronic constant current source.

The current was supplied from a controlled current source with an adjustable level up to about 5 mA dc, and with a driving voltage capability of 120 V. The operational amplifier in Fig. 1 will regulate its output voltage so that the voltage over R7 is equal to the voltage V over the potentiometer R2. Hence a constant current I is driven through the skin, so that $I = V/\text{R7}$.

3. Results

With the 10 µA resolution used in this study, we found no metal dependency for the thresholds of perception and the data given here are with mild steel. However, since this study only included a total of four measurement series on two test subjects, there are not enough data to claim that there is no dependency on the metal used. This is hence an interesting topic for further research.

The sensation around threshold was slowly developing and was difficult to discern from other sensations, e.g. the mechanical pressure of the electrode. The perception was a sensation of warmth or tingling. After the sensation was clear and the current was slowly reduced to avoid ac stimulation, the sensation then always remained for some time. The perception was found to be localised under the monopolar electrode, never in the tissue distal to the electrode. Figs. 2 and 3 show the results.

The results were identical for both hands on both volunteers within the 10 µA resolution chosen for the tested current levels. The dependency was according to the equation:

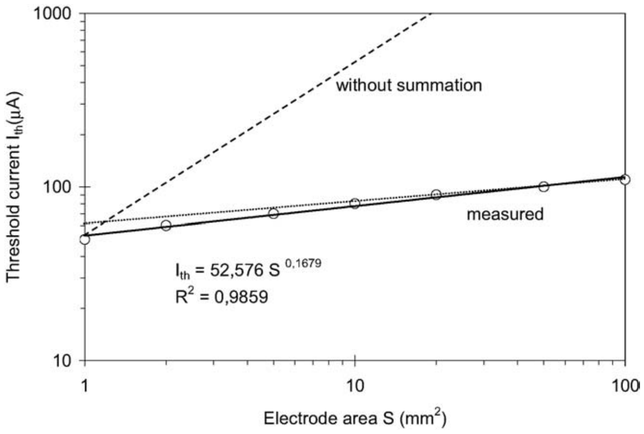

Fig. 2. Level of perception (current) as a function of electrode area. Circles are measured values and line is calculated regression. Dashed line shows expected behaviour without summation and dotted line shows values above 10 mm^2 extrapolated to smaller electrode areas.

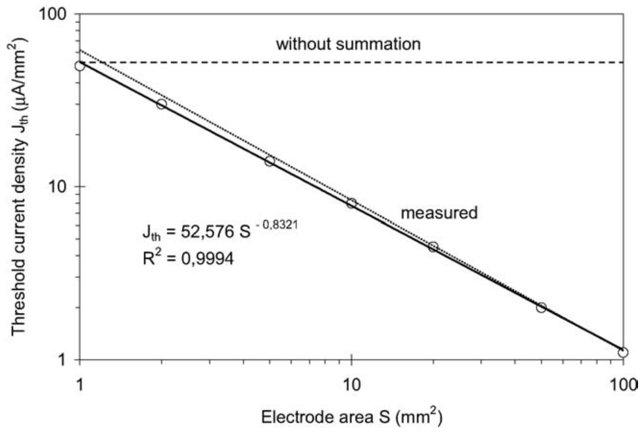

Fig. 3. Level of perception (current density) as a function of electrode area. Circles are measured values and line is calculated regression. Dashed line shows expected behaviour without summation and dotted line shows values above 10 mm^2 extrapolated to smaller electrode areas.

$$I_{\text{th}} = I_0 \cdot S^{0.17}$$

or

$$J_{\text{th}} = J_0 \cdot \text{S}^{-0.83}$$

where J_{th} is the threshold of perception current density, I_{th} the threshold of perception current, and S is the electrode area (mm^2). I_0 and J_0 are both typically 50 µA/mm$^{0.34}$.

The necessary driving voltage was recorded and found to be in the range 30–90 V, the larger values for the larger current densities and the start of current flow.

4. Discussion

As opposed to alternating current, direct current through tissue causes net ion migration, and these ions are depleted or accumulated at the electrodes. A sensation will start under one of the electrodes (anode or cathode), where the chemical composition will slowly change according to polarity.

When the current was slowly reduced to zero, the perception persisted for a long time, often several minutes or even hours. This indicates that the nerves are excited by chemical products of the dc current and not by the dc itself. The duration of the perception is dependent on the speed by which the tissue reverts to normal conditions, and this is dependent on tissue perfusion.

According to Figure 3, the highest current density threshold was 50 µA/mm^2. Could this lead to thermal effects? In general, the temperature rise per unit time in a tissue volume is

$$\frac{\Delta T}{t} = \frac{J^2}{\sigma c d}$$

where J is current density, σ tissue conductivity, c specific heat capacity and d is the density [6]. Using σ = 10 µS/m [6], c = 3500 J/(kg K) and d = 1500 kg/m^3 [7] as values for stratum corneum, the temperature rise per unit time becomes an extreme 48 K/s. Since the calculation does not take thermal diffusion into account, the real value is presumably significantly lower. However, this rough estimate clearly shows that the perception may be both of chemical and thermal nature.

The figures show that the level of perception is more dependent on the current I_{th} than the current density J_{th}. The reason for this is probably a spatial summation effect in the nervous system. As the electrode area is increased the current density is lowered, but more nerves and nerve endings are stimulated. Consequently the current threshold is not greatly altered when electrode area is changed. Figs. 2 and 3 also show that the summation effect is reduced for electrode areas below 10 mm^2 (see the dotted line in each figure representing an extrapolation of values for electrode areas greater than 10 mm^2). This is most probably due to thermal effects.

The electrolytic effect is a changed chemical environment very near to the electrode plate. However, there are no nerve endings in the stratum corneum. But although the dc conductance of the stratum corneum is significant [8,9], a substantial part of the dc current will also pass the sweat duct system [10], where the current density will be high due to the small cross section of the ducts. It is therefore more probable that the sensation is due to effects near the sweat ducts.

The perception of dc current shows how different dc and ac effects are in the human body [6]. This adds to the theories of the importance of dc effects in the body, e.g. closed endogenic dc circuits. Nordenstrøm [11] proposed the existence of closed dc circuits with the well conducting blood vessels serving as cables, e.g. a vascular–interstitial closed circuit. These dc currents can cause electro-osmotic transport through capillaries, and perhaps also perception.

5. Conclusion

The threshold of perception of dc current flow through the skin is not primarily dependent on current density, as would be expected. The threshold is more dependent on current, and the dependency is then $I_{th} = I_0 \cdot S^{0.17}$. Hence, we found a very significant spatial summation effect in the skin. We also found this spatial summation effect to decrease when the electrode area was reduced below about 10 mm^2, and believe this to be due to thermal effects. Perception under an active electrode with negative polarity was found to be non-reproducible, probably due to electro-osmosis. This is also an interesting topic for further research.

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