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Electrovibration, cutaneous sensation of microampere current

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The human threshold of sensation of 50 Hz current has hitherto been considered to be around 1 mA. A new sensing mechanism is reported which lowers the threshold about 3 decades. It is elicited when the skin slides on the current carrying conductor, and the sensation disappears when the skin is wet. The sensation is a feeling of vibration or increased surface roughness. The sensing mechanism has been shown to be due to electrostatic forces in the skin caused by the electric field in a poorly conducting stratum corneum. The mechanism is primarily potential dependent, and the absolute threshold of sensation has been found to be about 1.5 volt or 0.15 μA rms at 50 Hz. In practical daily-life situations it is shown that 82% of 40 test subjects were able to sense a current of 2 μA rms, 50 Hz.

Key words: Threshold of perception, electrophonic effects, skin senses, electrical safety

It has earlier been reported that man can sense less than 10 μA of 50 Hz current applied to intact "dry" skin (Grimnes 1977). This is in contrast to the widely accepted opinion that the threshold of sensation is around 1 mA, (review articles: Keesey et al. 1970, Sances et al. 1979). As will be shown, the difference is due to the way the current is applied to the skin. The usual approach is to use the palmar side of the hand, either with a firm grip around the current carrying conductor, or a finger tip contact, perhaps with a tapping movement (Dalziel et al. 1950, 1954). A much higher sensitivity is obtained on non-palmar skin sites, e.g. the knuckles of the fingers, if the skin is sliding on the surface of the conductor. At 50 Hz the feeling is a sensation of vibration. It is not disagreeable, and at threshold it disappears in frictional "noise". The lack of startling character can be one reason why it has not earlier been reported in the literature. Another reason can be the reduced effect when the skin is wet. Under dry conditions, and with 50 Hz currents larger than 10 μA, sharp pricks may be elicited (Grimnes 1977). This effect is quite different: it has an unpleasant character which may last minutes afterwards, and is evidently based on a completely different sensing mechanism. This effect will not be treated here. The purpose of the present paper is to examine the vibrating sensing mechanism and describe the various conditions under which it leads to perception. Because the sensation is elicited by electricity it will be called electrovibration.

METHODS

Electrodes. Four copper plates 20 cm × 5 cm were etched out on one printed circuit board of thickness 1.5 mm. The four areas were separated by a spacing of 1.5 cm. The surface was polished with finethreaded steel wool. An aluminium bolt (diameter 3 cm, length 12 cm) held in the hand was used as indifferent electrode.

Equipment. A lock-in amplifier (Princeton Applied Research, model 129) was used for capacitance measurement and low-level 50 Hz current reading. The circuit used for skin capacitance measurement with simultaneous application of a DC-potential is shown in Fig. 1. A similar circuit with the series capacitor replaced by a resistor and without the DC offset facility and the potential divider was used for the results of Fig. 6. The AC-signal source was a B & K sweep/function generator, model 3020. It has an internal gating facility with the on-off switching at zero potential cross-over. For amplitudes larger than 10 V the signal was amplified by a DC-coupled amplifier specially designed and built by the author. Specifications: gain 100, potential capability 350 V, current limit 3 mA, rise/fall time 10 μs. The result was recorded on a 2-channel storage oscilloscope, Tektronix model 7633. The same oscilloscope was used to record directly the potential-current relationship in the skin. Fig. 3 was obtained with a 10 kΩ shunt resistor for direct current reading. Fig. 4 was obtained with a 50 MΩ series resistor and a 230 MΩ resistor in series with the 1 MΩ input resistance of the oscillo-

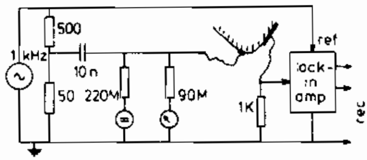

Fig. 1. Circuit used for skin capacitance measurement.

scope, the reference channel was the 300-volt output signal. The results of Fig. 4 show that the skin potential was in the range 50–100 volt peak. Because of the limited value of the series resistor (50 MΩ) the current source was not ideal, and the resulting current was not perfectly sinusoidal. An electronic random generator (dice box), specially designed and built by the author, actuated upon command one of the four electrode areas. It was constructed in such a way that information about which electrode that was actuated was not revealed to the test subject (necessary feature in the last experiment for determination of a practical threshold of sensation).

All results were obtained with one trained test subject, except the results of the last experiment for the determination of a practical threshold of sensation, which were obtained with 40 non-trained test subjects.

"Dry" skin is defined as the state of the skin when no electrolyte or conductive gel has been applied, after an adequate stabilising period during which the subject relaxes so that the sweat gland activity has reached a stable minimum and GSR-waves are not elicited at non-palmar sites (Grimnes 1982).

RESULTS

Some preliminary experiments were performed to reveal characteristic properties of the sensing mechanism. They were performed with a current source of about 7 μA at 50 Hz. The person under test let the knuckles of the fingers slide on one of the copper plate electrodes connected to the current source.

1. With dry skin the sensation was clear and vibrational. Often the sensation was strongest at the start of contact.

2. With wet skin, either artificially wetted or by sweating, the sensation disappeared or was strongly reduced. When isolating oil was applied to dry skin however, the sensation persisted.

3. When other metals than copper were tried, no difference could be noticed. It was even possible to elicite the sensation when the metal was covered with paint or a thin plastic film. Surface smoothness seemed to have a certain effect.

4. When the ear was held near the copper plate a humming sound could be heard when the finger moved along the electrode.

5. Both the vibrational sensation and the hum stopped when the sliding velocity was zero, but otherwise the velocity seemed to have only small influence.

6. The palmar side of the hand, even the finger tips, often gave poor and irregular response.

Experiment No. 4 proves that a conversion of electrical energy into mechanical energy takes place. The most probable conversion mechanism in dry skin is electrostatic forces caused by the electric field. The stratum corneum is responsible for the high impedance of the skin (Rosendal 1940, p. 118). At non-palmar sites it is about 10 μm thick, at palmar (and plantar) sites about 300 μm. This layer can be considered to constitute the dielectricum of a capacitor, with the capacitor plates formed by the electrode plate on one side and the well conducting layers of the skin on the other. In Fig. 2 the sensing situation is illustrated. When a potential is applied, the electrostatic force K compresses the stratum corneum. The magnitude of K is given by:

$$K = \frac{1}{2} \frac{S \epsilon}{d^2} u^2 \qquad (1)$$

where S = contact area, d = thickness of stratum corneum, u = instantaneous potential difference, ϵ = dielectric constant.

Because there are no nerve endings in the stratum corneum the compression will not be sensed. By moving the skin along the metal electrode another force perpendicular to the compressive force will arise, this frictional force F is given by:

$$F = (K + T)\,\mu \qquad (2)$$

where μ = coefficient of friction, T = contact pressure exerted by the human body.

μ has been measured in the range 0.2 (teflon) to 1.7 (damp skin) (Highley et al. 1977). It is therefore

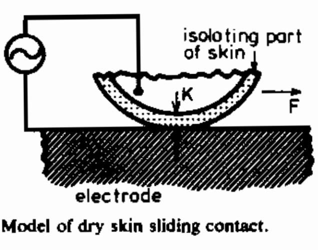

Fig. 2. Model of dry skin sliding contact.

an appreciable amount of transfer from the perpendicular compressional force to the tangential, frictional force. The capacitive current implies that ideally there is no electric power loss, the frictional losses are supplied by the muscles with the sliding movement. Without net supply of energy the electricity modulates the frictional force F by the variation of K in eq. (2). This explains the extremely high sensitivity of electrovibration. The dermis and subdermis are soft tissues, and with AC-potential the skin is periodically hindered by the periodically increased frictional force. By repeating experiment 1 with a very low frequency, e.g. 2 Hz, the hindrance can be directly visualized, the vibrational amplitude can be seen to be several tenths of a millimeter. The tangential periodic movement of the skin is sensed by the vibrational receptors. There are two sets of receptors for flutter-vibration in the skin (Verrillo 1966 and Mountcastle et al. 1967). The Pacinian corpuscles are very sensitive, situated deep in the skin and with optimal frequency response in the range 150–250 Hz. At lower frequencies below 40 Hz (they extended the measurements down to 2 Hz) other and more superficially situated receptors take over.

The results of experiments 1, 3, 4 and 5 are clearly in agreement with the electrostatic theory. Experiment 2 refers to the effect of an intermediate layer between the skin and the metal electrode. If the layer is isolating oil, the only effect will be increased distance d (eq. (1)) and a possible change of the coefficient of friction. The most important point is however that the compressive force K is still acting from the electrode plate. This is not the case if the intermediate layer is conducting, the compressive force is then acting between the well-conducting part of the skin and the upper surface of the conductive layer. If the layer is a liquid film the frictional force F is not modulated any more, we will have a constant, viscosity-determined, frictional force. The conductive layer will also increase skin admittance and consequently reduce the potential difference u across the stratum corneum when supplied from a current source. Because the electrostatic force K is proportional to the square of the potential difference u, eq. (1), this also strongly reduces electrovibrational sensitivity.

Experiment 6 shows that the fingertips often have poor sensitivity, in spite of being the most sensitive site with respect to mechanical vibration (Wilska 1954). Two reasons for the poor response will be emphasised. Palmar skin is more than 10 times thicker than non-palmar skin, accordingly the electrostatic force is reduced by more than 1/100, eq. (1). Even more important is perhaps the perpetual sweat gland activity which is independent of thermal stress (Grimnes 1982).

To further test the validity of the electrostatic conversion theory a control of the magnitude of the electrostatic force was done. Eq. (1) can be rearranged:

$$K = \frac{1}{2}\frac{C}{d}u^2 \qquad (3)$$

where C is the capacitance of the stratum corneum under the electrode.

By simultaneously measuring K, C and u, and assuming $d = 10\,\mu m$ it is therefore possible to check whether the mechanical forces are correctly described by eq. (3) under dry skin conditions. The set-up of Fig. 1 was used. With a small metal button with a diameter of 3 mm and weight 0.2 g it was possible to make it stick to the skin and bear its own weight with a DC-potential of about 100 V. Positive polarity was used to impede skin breakdown (Grimnes 1983*a*). The corresponding capacitance was measured to 4 pF and the conductance 10 nmho (1 kHz). These values are in agreement with eq. (3), and indicate that the electrostatic theory is correct. Moreover it indicates that the electrostatic forces are a dominant mechanism with dry skin. This conclusion is also strengthened by the fact that galvanic, electrolytic contact was not a prerequisite to sensation.

Some additional results which may elucidate characteristic properties of the sensing mechanism will be reported. As already mentioned it was possible to hear a sound during the sliding procedure at higher intensities with the electrode used. This sound was particularly clear around 2000 Hz, a frequency too high to give a vibrational sensation with dry skin. This sound production was rather uniformly distributed over the skin of the extremities, with the exception of palmar skin. The vibrational sensitivity at 100 Hz seemed to be more dependent on the skin site than the sound production.

At high intensities it was a marked change in the perception of vibration towards a lower pitch. At 50 Hz for instance, it was sometimes possible to get the impression that the vibration had a frequency of just a few cycles per second.

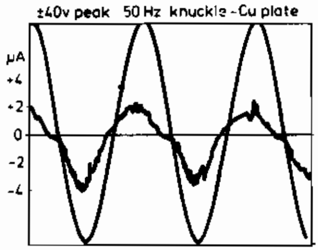

Fig. 3. Skin current with sliding knuckle contact, potential source.

A small, smooth electrode of 20 mm^2 was drawn along the skin to examine the perception when skin contact site was continually changed. Under such conditions the sense of vibration was more difficult to discern from the perception without applied current.

Skin admittance, sweat gland activity and electrovibrational sensitivity

In the proposed model the stratum corneum constitutes the dielectricum of a capacitor formed by the electrode plate and the deeper, well-conducting layers of the skin. The corresponding electrostatic capacitive susceptance is therefore the minimum of skin admittance. Additional electrolytic shunt admittances from filled or semifilled sweatducts and special AC-current paths are inevitable and usually dominate. This is illustrated in Fig. 3 and Fig. 4 which show typical examples of current and potential curves with a potential source and a current source respectively. Dielectric breakdown of the electrostatic skin capacitance is not likely below 100 V (Grimnes 1983*b*), the non-linearity seen in Fig. 3 and Fig. 4 is therefore due to the electrolytic admittance part. Electro-osmotic transport of liquid from deeper, vascularised skin layers increases electrolytic admittance (Grimnes 1983*a*). Fig. 4 shows that with negative polarity the potential is limited to about 60 volt by such electro-osmosis. Just as sweat gland activity electro-osmosis will reduce electrovibrational sensitivity. However, if the current is capacitively coupled (as is often the case with leakage current of appliances), a DC-potential will build up by rectification and prevent further electro-osmosis.

Sweat gland activity depends on physical activity, personal clothing and ambient temperature. So does skin admittance, but not in the same way. The dependences are very complicated, particularly because of the variable delay between a change in one parameter and the corresponding effect. For instance, in a particular case, skin admittance may double in a few seconds when the person under test just lifts his hand (Grimnes 1982). Accordingly the electrovibrational sensitivity in a practical situation is unpredictable, as will be further illustrated below.

Absolute threshold of sensation

With a sinusoidal signal $u = \sin \omega t$, eq. (1) can be written:

$$K = \frac{1}{4} \frac{S \epsilon}{d^2} U^2 (1 - \cos 2\omega t) \tag{4}$$

which shows that the mechanical vibration occurs at twice the signal frequency. The second harmonic can be strongly reduced by applying a DC-offset potential, so that $u = U\,(1 + \sin \omega t)$. Then

$$K = \frac{1}{4} \frac{S \epsilon}{d^2} U^2 (3 + 4 \sin \omega t - \cos 2\omega t) \tag{5}$$

The threshold of sensation was accordingly measured both without DC-offset (marked o on Fig. 5 and Fig. 6) and with DC-offset (marked +). The data with DC-offset must be compared with mechanical vibrational data found in the literature.

The threshold of sensation is reached when the electrovibration becomes approximately equal to the "noise" from frictional, non-modulated forces. An unexperienced test subject must first learn what kind of perception we are dealing with. This can be done by starting at a relatively high current level, e.g. 10 μA rms, 50 Hz. As the test proceeds the threshold of sensation will gradually diminish, mainly for two reasons:

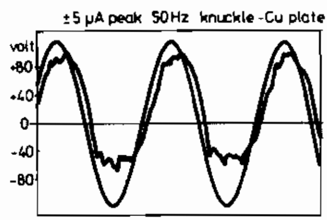

Fig. 4. Skin potential with sliding knuckle contact, current source.

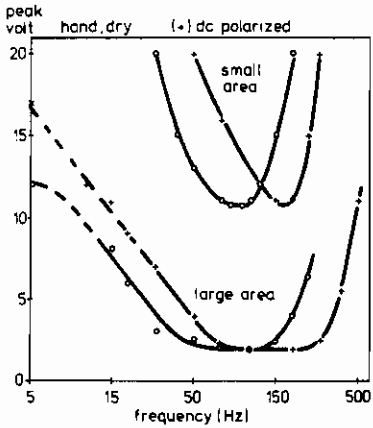

Fig. 5. Absolute threshold of perception, potential source. Dorsal side of the hand, one trained subject.

1. After the person under test is seated the reduced sweat gland activity will gradually increase the electrovibrational sensitivity. After a certain period even galvanic skin response (GSR) disappears at non-palmar skin sites (Grimnes 1982): dry skin condition has been attained.

2. The test subject will undergo a learning process, both perceptional and methodical. The most important methodical parameter is to find, and keep, the most sensitive skin site and the optimum contact pressure and contact area.

The threshold thus becomes a question of testing time, and this can go on for hours. The absolute threshold of sensation has therefore been found with one well-trained subject.

Fig. 5 shows the result obtained with one of the copper plate electrodes connected to a source of negligible internal impedance, i.e. a potential source. Highest sensitivity was obtained with large contact area (≈300 mm^2). Small contact area (≈30 mm^2) not only showed higher threshold (indicating an areal summation process somewhere in the sensing system), but also a stronger frequency dependence. Below about 40 Hz it was better to reduce contact pressure so that the skin could vibrate more freely. The perception changed, an additional learning process was necessary, and the threshold was more difficult to define. The results below 40 Hz have therefore been stippled on Fig. 5 (and Fig. 6). Above 40 Hz the AC-potential was gated on and off in order to determine the threshold as clearly as possible, each period lasting 0.5 s.

Fig. 6 shows the result with a current source, above 40 Hz the current was gated. As current is not the primary parameter of electrovibration, the data will be strongly influenced by skin admittance. It was found advantageous to keep skin admittance low by using small contact area and light contact pressure. Because of this the results presented in Fig. 6 must be compared with the small area values in Fig. 5. The largest difference between Fig. 5 and Fig. 6 is in the low frequency end, the frequency region of maximum sensitivity is wider with the current source. This is caused by the frequency dependence of the admittance due to skin capacitance. Skin potential increases at lower frequency and counter balances the reduced sensitivity shown in Fig. 5. It is concluded that the absolute threshold of sensation is extremely low, about 0.2 μA peak, corresponding to about 0.15 μA rms.

Practical threshold of sensation

The absolute threshold values are of theoretical interest only. Usually such small intensities will not be noticed. To find more useful figures for daily life situations, 40 test subjects have been measured with a rapid "walk-in" procedure without letting the person under test sit down and without waiting for maximum sensitivity. No current gating was used, and the 40 test subjects got no particular training time. They were asked to use the knuckles of the fingers, and the test was done immediately

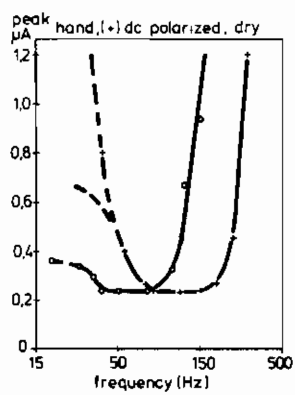

Fig. 6. Absolute threshold of perception, current source. Knuckles of the fingers, one trained subject.

Table 1. *Number of test subjects being able to sense different 50 Hz-current levels, knuckles of the fingers*

Current µA rms	Test subjects Number	%
65	40	100
25	39	97
12	37	92
6	36	90
2	33	82

after the arrival to the test bench and while they were standing. The test was therefore not carried out with "dry" skin as defined in this paper, but nevertheless with non-wetted skin. Results with test subjects having washed their hands or entered from rainy weather the last quarter of an hour were omitted. Immediate thresholds in such cases were often higher than 65 µA. The board with the four electrodes connected to the electronic dice box was used, and the test subject was to tell which of the four electrodes were current carrying. The starting current level was 12 µA and 4 trials were given at each current level. The five levels, 65, 25, 12, 6 and 2 µA rms were used. The level was decreased until the first incorrect answer was given. If the test subject declared that a wrong statement had been given, two new series of 4 trials at the same level were given. If these two series were correct the level was accepted. Current levels below 2 µA were not tried even if the test subject declared that the sensation with 2 µA was very clear. The tests were performed during the months July to September. 40 test subjects of both sexes and age from 6 to 79 were tested. Table 1 shows the results. No particular age or sex dependence was evident. As already mentioned the different threshold levels were probably due to different degrees of skin dryness, although a certain influence from skin thickness cannot be excluded.

DISCUSSION

The electrostatic conversion mechanism in the skin is known in the field of acoustics. It belongs to a family of effects called electrophonic effects, that is auditory sensation from alternating current flow through the head (or other part of the body). It was concluded that four possible effects could be involved (Flottorp 1953, 1976): electrostatic conversion (Johnsen-Rahbek effect), electrocapillarity, modulation of adhesive forces, electrostriction. A fifth possibility can be added: electro-osmotic pressure (Glasstone 1946). Our results indicate that the electrostatic conversion mechanism is the dominant factor in electrovibration.

The frequency dependence of the DC-polarised threshold values is in general agreement with data given in the literature for mechanical vibration (Bekesy 1959, Mountcastle et al. 1967, Geldard 1972). The narrow frequency band with small contact areas is rather in contrast to the results with direct mechanical excitation (Verrillo 1963, Geldard 1972). This may be due to the difference between the contact with a mechanically vibrating plate and the damping effect of a mechanically more passive electrode plate. Also, it has been reported that compression waves and shear waves propogate differently through tissue (Gierke 1960). In addition, skin site dependence must be considered, the large and small area results of Fig. 5 are not from the same site of the hand. Wilska (1954) reported not only different thresholds, but also different frequency dependence of different skin sites. The same was reported by Talbot et al. (1968). The last group reported (Mountcastle et al. 1967) the low frequency (below 40 Hz) sensation to be localised more to superficial skin layers on the dorsal side of the hand. This is in agreement with our results.

The perception of lower pitch with higher intensities is in accordance with reports of mechanical vibration (Bekesy 1959).

The threshold of perception of 1 mA accepted up to the present (Dalziel 1950, 1954) is presumably based on direct electrical excitation of nerves and nerve endings. Forbes et al. (1935) examined the threshold with extremely small electrodes down to 0.015 mm^2 contact area. The threshold was about 40 µA, with 10 mm^2 it was above 100 µA. Direct electric excitation of nerves or nerve endings is therefore not likely at the electrovibrational threshold.

Fig. 5 shows that there is a summation effect in the skin because larger areas implied lower thresholds. This is in accordance with the results with mechanical vibration. Sensitivity is proportional to the square root of the contact area in the range 1–500 mm^2 (Verrillo 1966), our Fig. 5 is roughly in accordance with this. Even if the time effect was small, our results indicate that there is not only a spatial summation, but also a summation in the time domain.

The knuckles of the fingers proved to be sensible sites of electrovibration, although sound loudness was not particularly strong there. It is reasonable to believe that in addition to the summation effect over area there is also a spread of vibration via the subjacent bones.

The leakage current of earthed electrical appliances is often larger than 2 µA and in such cases the result of the statistical threshold test shows that in ordinary, in-door daily life situations a broken earth wire can be sensed by more than 80% of the personel. Electrovibration is therefore a valuable sense with respect to electrical safety in such critical areas as the operating theaters.

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