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Evaluation and comparison of 50 Hz current threshold of electrocutaneous sensations using different methods

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Abstract: Leakage currents, tiny currents flowing from an everyday-life appliance through the body to the ground, can cause a non-adequate perception (called electrocutaneous sensation, ECS) or even pain and should be avoided.

Safety standards for low-frequency range are based on experimental results of current thresholds of electrocutaneous sensations, which however show a wide range between about 50 μA (rms) and 1000 μA (rms). In order to be able to explain these differences, the perception threshold was measured repeatedly in experiments with test persons under identical experimental setup, but by means of different methods (measuring strategies), namely: direct adjustment, classical threshold as amperage of 50% perception probability, and confidence rating procedure of signal detection theory. The current is injected using a 1 cm^2 electrode at the highly touch sensitive part of the index fingertip.

These investigations show for the first time that the threshold of electrocutaneous sensations is influenced both by adaptation to the non-adequate stimulus and individual, emotional factors. Therefore, classical methods, on which the majority of the safety investigations are based, cannot be used to determine a leakage current threshold.

The confidence rating procedure of the modern signal detection theory yields a value of 179.5 μA (rms) at 50 Hz power supply net frequency as the lower end of the 95% confidence range considering the variance in the investigated group. This value is expected to be free of adaptation influences, and is distinctly lower than the European limits and supports the stricter regulations of Canada and USA.

Key words: Electrocutaneous sensation, Non-adequate stimulation, Adaptation, Psychophysics, Cutaneous mechanoreceptors, Human hand, Safety guidelines

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INTRODUCTION

Measurement of the perceptibility of electrical currents by the skin sensors is a convenient way to determine maximum allowable leakage currents or contact voltages respectively.

The perception of current passing through the skin is not harmful, but unpleasant. The prickling and itching due to non-adequate stimulation by electrical currents is called an electrocutaneous sensation (ECS). The perception increases with higher amperages to pain. Higher currents can stimulate nerves and muscles and may lead to a life-threatening situation. Hence, the perception of a small current can serve as a warning signal. But even small currents may lead to a secondary accident, caused by the shock reaction owing to an unexpected perception: A perceptible current should be avoided.

Recent developments have shown that an electrocutaneous stimulus can be used as an aid for impaired persons [“electrotactile displays” (Kaczmarek *et al*., 1991)] or as a noise-free signal in modern communication electronics [like “electroshock-ringing” mobile phones (Patino *et al*., 2006)].

While the measurement of a leakage current flowing from a device through a human body to the ground is easy to realize, and to use the threshold current of electrocutaneous perceptions as an upper limit of an acceptable leakage current is immediately reasonable and accepted both by researchers and practicians, we find an unsatisfactory wide range of current thresholds both in literature and in legal regulations.

Current thresholds of ECSs are, at first glance, easy to measure quantity; their practical value concerning security limits is evident. So it is no wonder that several authors report these thresholds; but the values are in a surprisingly wide range from about 50 μA (Levin, 1991) up to greater than 1000 μA (Dalziel and Mansfield, 1950; Dalziel, 1954) at net frequency.

Therefore, we first try to collect all factors influencing the resulting threshold.

Since beyond different experimental setups the measurement method itself may influence the result, we repeat the measurements using identical experimental setup. This allows a direct comparison of different, both the classical and modern, methods for the first time.

THRESHOLD VERSUS STIMULUS LIMEN

For persons not familiar with perception psychology, it may be surprising that one cannot define one single threshold. The closest definition in common language is the threshold of first perception of the electric stimulus. However, this threshold usually does not coincide with the threshold of fading/last perception. This is obviously quite dissatisfying as a safety evaluation. We determined these two types of thresholds using the direct adjustment procedure.

If the medical doctoral speaks about "the" threshold, he usually refers to the value where 50% of all given stimuli are detected. Though this probability p=0.5 threshold is quite unsatisfactory as well since it accepts that one may perceive an ECS every second time one touches an electrical device, this definition becomes quite popular, sometimes with arbitrarily lowered probabilities p=0.05 or p=0.01. To determine this threshold, we developed a new method significantly faster than the traditionally used methods.

The signal detection theory (SDT) denies the idea of the existence of the threshold assuming that a stimulus is always perceived and that the test person will make an active decision whether to judge this as a perception or not. Consequently, the value resulting from the confidence rating procedure is not called a threshold but the stimulus limen. Though this is quite complex, we tried to give a short idea of it.

FACTORS TO BE CONSIDERED

We have to consider that the thresholds depend on three groups of variables, where only the first group, the technical variables, can be controlled strictly.

Technical variables

1. Frequency

Most authors used 50 Hz or 60 Hz, the power net frequency of Europe-Asia and North America, respectively.

2. Signal shape

Sinusoidal currents are most often used, but some authors used pulsed currents (square-wave currents) like those used in physical therapy.

3. Active electrode area

The active area of the electrode surface directly controls the resulting current density within the tissue, in which the stimulated receptors are embedded. So, an increase of the active area results in higher current thresholds.

4. Place of current application

The anatomy of the skin changes with the skin region, and so does the current threshold. This is due to a change in thickness of the individual skin layers, where mechanical stressed regions develop thicker layers of fatty tissues, due to the different build-up of hairy and hairless skin, but due to the different innervation density as well. We chose the fingertip, since this region has the highest innervation density.

5. Shape of electrode

The outer form of the electrode may also change the resulting current density at the place of the receptors and thus the current threshold.

6. Materials of electrode and electrode paste

The materials of the electrode and electrode pasts or saline solutions etc. are selected to make a small electrode-skin resistivity. However, especially the latter, may change the conductivity of the outer skin layers resulting in a scheme of conductivity which does not correspond to the everyday situation. These auxiliaries may decrease the current threshold if the current can easily flow into deeper skin layers, while it can also increase the current threshold if an exaggerated moistening of the skin partly short-circuits the active and counter electrode.

7. Moisture of the skin

The skin humidity will change the current threshold as described before; however, since sweating is a natural process we have to consider the changes which will result. This is why we used dry electrodes and moisturing of the skin as well.

Individual physiological variables

1. Thickness of the skin layers

The individual skin layers develop depending on mechanical strain. The stratum corneum, the outer dead skin layer, has a low conductivity (Southwood, 1955; Whitton and Everall, 1973; Whitton, 1973) and will significantly influence the current distribution within the skin.

2. Other anatomy

The overall anatomy of the body parts considered, like the diameter of the arm or of the finger, relates to the size of the volume conductor passed by the stimulating current.

3. Innervation density

The interindividual variation of the number of skin receptors may also influence the threshold, although this variable is not detectable.

Individual psychological variables

1. Intention

We should not forget that the determination of a threshold depends on the co-operation of the test person. Using control methods like blind trials the investigator has to check the “reliability” of the test candidate.

2. Stress/concentration

The test situation is felt like an exam situation by the test person; this means that she/he is stressed, which will result in a change of concentration.

Since the threshold will depend on the factors mentioned above, it is nearly impossible to compare the results of two authors with different experimental setups. So we applied the most common classical determination methods again, as well as investigations methods of modern signal detection theory.

GENERAL EXPERIMENTAL SETUP

To simulate the flow of leakage currents into a test person under reproducible conditions, an experimental setup (Fig.1) was developed for the determination of the perception threshold current of electrocutaneous sensations. The experiments were carried out at the index fingertip of the test person, because the fingertip: (1) can in everyday life come most probably into contact with leakage currents, (2) has the highest innervation density (Johansson and Vallbo, 1979), and (3) has loss-free synaptic interconnections (Vallbo and Johansson, 1984).

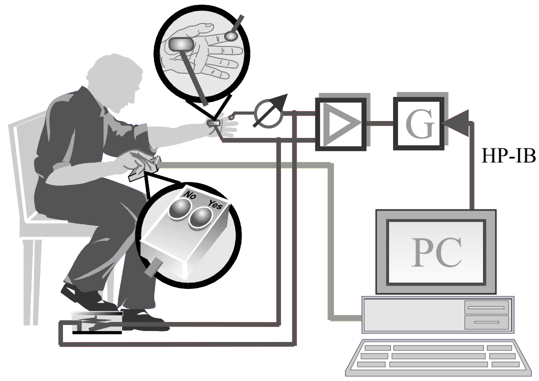


Fig.1 Experimental setup: the PC generates the test current via a function generator and a current generator. The active electrode is placed onto the fingertip (blow-up insertion). By releasing of a kick switch, the test person can short-circuit the leads and so stop the test current

HP-IB: Hewlett-Packard interface bus

The current was injected using adhesive electrodes from medicotest (type 0831A/4), where the injecting face of the active electrode was reduced to 10 mm×10 mm using a mask of plastic. The active electrode was fixed on the index fingertip.

Compared to an electrode which can be strapped down, an adhesive electrode has the advantage that it causes no pre-irritation of skin through pressure, which can influence the perception. No contact gel or anything similar was used, because it will soften the skin differently and frequently contains irritating substances, stimulating the blood circulation which would be able to influence the perception, too. The silent electrode, placed on the palm surface, was 50 mm×90 mm (medicotest type 4031A/4).

The currents were generated by means of a function generator (AFG-8011 from Temec) and a post-connected voltage-controlled amplifier. The function generator was controlled via the Hewlett-Packard interface bus (HP-IB) with the aid of the program VEE (initially by Hewlett-Packard measurement technology, now Agilent).

A number of safety precautions were taken leading to a greater acceptance as well as minimizing fear of the persons undergoing the test. The amplifier was planned as galvanic separate constant current generator which delivers low-frequency currents up to 700 μA (rms) independent of skin and transfer resistances. We chose a sinusoidal current at the European and Asian net frequency of 50 Hz. By releasing a kick switch, the test person could short-circuit the test circuit at any time and therefore could end the excitation if this should become unpleasant. The entire structure (including computers) was protected by a residual-current-operated protective device, too. All investigations took place inside a quiet room with controlled temperature. In the case of yes/no-task, the test person holds a small control box in the hand, with push-buttons for the answers "yes" and "no", as well as—positioned on the side—a button for aborting the test.

MATERIALS

Data were obtained from 21 to 34 years old healthy volunteers. All test persons were right-handed while the test was carried out on the index fingertip of the left hand. They did not consume medicaments or drugs. No actual injuries or older severe injuries were found in the tested left hand.

Four test persons underwent the investigation of direct adjustment, two females and two males. Four male test persons carried out the interval maximization procedure. Three test persons, one female and two male candidates, took part in the adaptation measurement test series.

The tests following signal detection theory are the most time-consuming investigations. Eleven test persons started the test procedures, but only six completed the full series of investigations. The remaining five persons withdrew due to the high time burden or because the needed strong stimulus could not be reached (see below). Of the persons continuing the series, three were females and three were males. Three of them (one female, two males) were willing to continue in a second investigation.

GENERAL TESTING PROCEDURE

At the beginning of a series of experiments, a questionnaire was filled out by the test person. Besides age, weight, etc., they were asked to make a subjective appraisal of their well-being and concentration capability, which had to be weighed on a 5-point scale. Test persons who had recently taken medicine or drugs, lacked sleep, and had injuries in the finger hand region were excluded from the experiments. After this, the test person was introduced to the task, the safety of the experiment was pointed out, and finally the plug and electrodes were positioned.

Four types of experiments were conducted: (1) direct adjustment; (2) interval maximization; (3) adaptation measurement; (4) confidence rating.

Each individual series of experiments was designed for a maximum length of 20 min in order to avoid over-exertion. After a short break, the test person could decide whether he wanted to take part in a further series. After each series, a questionnaire on their personal feeling was completed corresponding to that at the beginning. As a rule, three series were performed in succession, which corresponds to a working time of approximately 1 h.

MEASURING STRATEGIES USED

This section describes the different measurement procedures and their underlying strategies. Following the linguistic usage of perception psychology, each amplitude >0 is called a signal.

Direct adjustment procedure

In this test series the test person had to adjust the amperage value of the test current by using a hand wheel: (1) first perceived; (2) just not perceived.

In consecutive test series, the test person followed these instructions:

1. One should react as sensitively as possible, i.e. in the case of suspicion of an irritation, announcement

(acknowledge the stimulus perception) should already occur.

2. A signal should only be announced in the case that a signal trial was observed certainly.

3. After these two passes the test person was instructed to find a "mean value", a value between these two extremes, by means of the experience collected.

This gives a total number of six current threshold values determined by each test person.

Interval maximization procedure

The interval maximization method was developed by us to gain a classical (threshold-based) method corresponding to the method of constant stimuli or the method of limits while reducing the investigation time needed.

Increasing and decreasing stimulus strengths were offered to the test person starting from a supposed stimulus threshold value (initial value). The test current was switched on and off at a 1 s cycle in order to allow the test person an easier assessment of the perceptibility. The test person indicates whether he observes a stimulus or not.

The number of the trials N per amperage was increased step by step starting from 3 trials via 5, 10, 15 to total 20 trials. The increment of the amperage ΔI was 10 μA. The lower value was decreased until the weakest stimulus was so small that it was never perceived (p=0). The higher value was raised until the stimulus was always noticed (p=1). Consequently the interval between secure non-perception and secure perception was extended until it encompassed the entire transition region. Because the signal is changed according to the answers of the test person, no general stimulus order can be given. However, we point out that strong stimuli are followed by weak stimuli (and vice versa).

Let $n(I)$ be the number of positive responses that a stimulus was detected at the amperage I. Then $p(I)=n(I)/N$ is the probability that a current will be detected. We concentrate on the interval $p\in[0;1]$ with the additional conditions $p(I)=1{:}I$ minimal and $p(I)=0{:}I$ maximal. Values outside this interval were considered redundant: Measurements below will return a constant non-perception, measurements above a constant perception and therefore no new information. They are omitted in the test person experiment to shorten the measuring time. The advantage of the interval maximizing method compared to the method of constant stimuli is that the test interval does not need to be determined before the test person experiment but only one value must be assumed from this interval.

Adaptation measurement procedure

If an irritation by means of current leads to an adaptation as an adequate irritation does, a strong stimulus can have a negative effect on the perception of a following small stimulus or completely mask it.

A typical signal sequence is sketched in Fig.2. The pause time t_P between these two current signals, the strength of the preceding, stronger current I_M and its duration t_M influence the perceptibility of the second stimulus of the strength I_T and the duration t_T if an adaptation is existent.

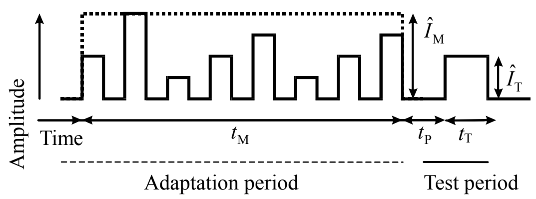


Fig.2 The typical amplitude course of a classical test can be estimated by a worst case signal (dashed line)

In two examination series, the existence and influence of adaptation were examined depending on the preceding, adapting signal I_M of duration t_M and the pause time between the preceding and the test signal t_P.

1. Dependency on strength and duration of the preceding signal

The influence of the signal strength I_M and the duration t_M of the proceeding signal are considered.

After administering a signal of amperage I_M for the length of time t_M, the current source is switched of for the duration t_P. Then, test current of initial strength I_T is allowed to flow and is increased by ΔI steps until the signal is detected. We assume that the time needed for detecting the threshold will not have a strong effect on the adaptation state.

2. Dependency on the pause time

In these series, the amperage I_M and duration t_M of the preceding signal are fixed and the pause time t_P is varied. The search for the threshold is done using the divide et impera procedure, also known as binary search. A value of 0 μA is assumed as the lower border of the threshold, and the upper border is chosen as 500 μA. The amperage of the test signal is the mean value of the test interval (thus 250 μA the first time). If the test person indicates no perception, the mean value is the new lower border of the interval (the next test current would be 375 μA), otherwise, the mean value is the top border of the interval (next test current: 125 μA), and so on.

Confidence rating procedure

The signal detection theory assumes that a signal (stimulus) is always perceived, in contrast to the classical theory, which assumes that stimuli below a certain (and determinable) threshold cannot be perceived (Macmillan and Creelman, 1991; Schmidt and Thews, 1995). Following the signal detection theory, the stimulus (or signal) S adds up to a permanent noise N which is produced e.g. by spontaneous depolarization of the receptor cells, resulting a shift in the probability of the occurrence of a signal with a certain strength (Fig.3). The test person now actively evolves a criterion C: below which all signal occurrences are neglected, above which C recognized. The main difference from the classical threshold theory is that this criterion C can be changed at any time. As it can be seen from Fig.3, C can never be chosen so that a perfect detection of external signals can be realized (i.e. no missed signals and no false alarms). The assessment of the total signal (signal and noise) will result in a decision (Macmillan and Creelman, 1991).

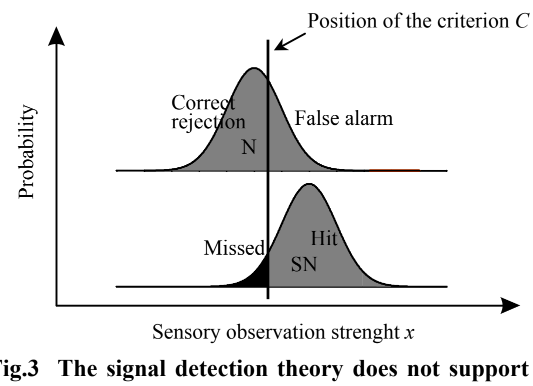


Fig.3 The signal detection theory does not support a single threshold, but one (or even more) decision criterion which can be actively changed by the test person

In the confidence rating procedure, the task of the test person is to rank the intensity of the perceived stimulus on a scale of one to five points. Following the signal detection theory, the test person will develop criterions to classify the stimulus strength (Gescheider, 1976). Since our scale is symmetric, the test person can state that it is impossible for him to decide whether there was a signal or not by giving 3 points.

During a session, signal trials with a fixed (rms) amperage of the signal I_S as well as no-signal trials were presented in a random order, indicated by an acoustic signal. It should be pointed out that the test person was not told that the signal has a constant intensity, but he/she was informed about the signal probability p_S. For each amperage a total of 200 judgments were collected in one task. Several passes with different amperages were carried out.

In a second investigation, the skin of the volunteers was washed using physiological saline solution, so that the skin was drenched. The confidence rating procedure was then carried out as described before.

RESULTS

Direct adjustment procedure

The data listed in the Tables 1 and 2 show that the values of the first perception and of the last perception differ for a given sensitivity. An absolute threshold where the sensation flips from "no perception"

Table 1 Results of the direct adjustment procedure. Listed data are the subjectively determined threshold amperages (rms) at 50 Hz for the first perception of ECS

Test person	Sex	Threshold current / μA (rms) at a quality of perception		
		Weak	Mean	Sure
A	F	140	260	265
B	F	130	175	190
C	M	245	280	380
D	M	195	320	330

Table 2 Results of the direct adjustment procedure. Listed data are the subjectively determined threshold amperages (rms) at 50 Hz for a just fading perception of ECS

Test person	Sex	Threshold current / μA (rms) at a quality of perception		
		Weak	Mean	Sure
A	F	115	225	240
B	F	120	120	125
C	M	205	220	350
D	M	180	295	320

to “clear perception” does not exist. All amperages were rounded to 5 μA. If the subjective assessment of the test person would have no influence, the three values in the two tables would have to be (almost) identical.

However, it appears that they differ up to 100% (test person A). The classification carried out by the test person could not decrease a tendency in assessment: the values for mean perception certainty are normally higher than the arithmetical mean of the two limiting values. The test person C both for first perception and for last perception, and the test person B for last perception generate exceptions here. We have to notice that the threshold of disappearing perception is partially clearly above the limit of first perception. This effect is in the case of “surer” perception, which is at higher current values, more strongly distinct. For example, test person C indicates inability to observe a signal certainly in the case of 350 μA, on the other hand, the values for first perception and mean perception are as low as 245 μA and 280 μA, respectively.

These points toward an adaptation to the non-adequate stimulus which lets the threshold rise within a given time. Since the current was decreased after first perception, all values for dying-away perception are lower than those for first perception in the case of the same sensitivity.

These punctual measurements are unsuitable for determining the threshold. To obtain a meaningful value, one must either enlarge the group of test persons in order to take the mean [a procedure which was also used in (Tan and Johnson, 1990)] or the threshold is defined as amperage with a perception likelihood of 50%, as normally done in physiology. The latter course was chosen here, and will be described in the following section.

Interval maximization procedure

Following the classical theory of an absolute threshold, the dependence of the probability p that a signal was noticed by the test person should show an ogive when drawn against the stimulus strength which is the amperage I.

If the equation

$$p(I)=\frac{-100\%}{1+\exp[(I-I_{0.5})/s]}+100\% \quad (1)$$

is used to describe the psychometric function by means of a p=0.5 current threshold $I_{0.5}$, and a reciprocal rate s, the values listed in Table 3 comprise the result for the four test persons.

Table 3 Results of the interval maximization procedure. Listed data are the parameters of the psychometric function of the individual test persons

Test person	$I_{0.5}$ / μA	s / μA	R^2 / 1
A	177.8±0.9	6.962±0.783	0.9777
B	214.2±2.8	22.894±2.857	0.8865
C	209.6±2.8	18.552±2.866	0.8683
D	193.9±3.7	18.888±3.802	0.7894

$I_{0.5}$: Amperage with a perception probability of 50% (and standard error); s: Reciprocal rate (and standard error); R^2: Coefficient of determination

This result also partially explains why the quantitative analysis of the threshold was so difficult for the test persons: the transition region, so-called “grey zone” between no perception on the one hand and clear perception on the other hand, is distinct. While the result for test person A in Fig. 4 can be described by the classical theory, the measurement of test person D, shown in Fig.5, shows that the curve is only described very unsatisfactorily by a sigmoidal curve. Clear drifts occur here between measured curve and the approximation function, the correlation coefficient is small (Table 3). These drifts cannot be explained by an adaptation.

An adaptation leads to a relocation of the psychometric function to higher values where appropriate, the distribution rate may also change, since small amperages are not always covered, therefore the

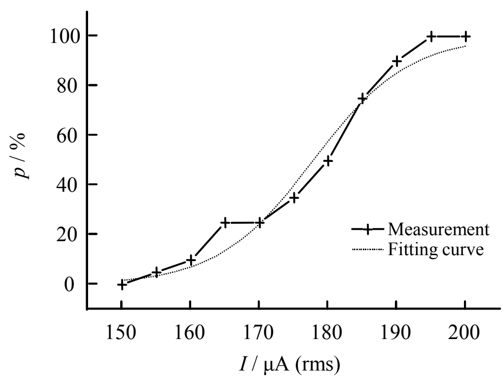


Fig.4 Probability of a perception depending on the signal intensity (amperage) for test person A. This measurement can be described using the classical threshold theory

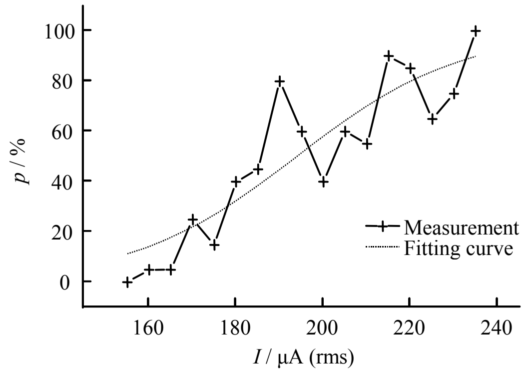


Fig.5 Psychometrical function of the test person D. The measurements differ clearly from the predicted curvature form. The application of classical theory is questionable here

ogive will become wider. Consequently, the found drifts cannot be explained by the parameters flowing into classical theory. Individual, subjective parameters have to be considered. For example, the test person changes the assessment of the stimulus intensity depending on stimulus strength during the examination.

This means that the decision whether the test was person's response to a question whether he might observe an ECS or not, does not depend on the respective signal trial alone.

We want to emphasize that the calculation of a mean value of all measured results (as usually done) will hide these variations. The resultant average value is higher than the perception threshold value in the case of most sensitive perceptions. But the latter should be used regarding safety examinations.

The classical theory of an absolute threshold fails to describe the perceptibility of ECSs.

The reason why the objective judgement of the stimulus was so difficult for the test persons to describe was that ECSs could easily be confused with a mechanical stimulus, like an itching under the electrode or an unavoidable tugging at the cables when the body is moved slightly.

Certainly a quantitative analysis of an (unsure) individual absolute classical threshold for a huge number of test persons and subsequent calculating the mean can lower the error of the entirety.

This may suggest a secure determination of a basis for a corresponding safety consideration, as Tan and Johnson (1990), Leitgeb and Schröttner (2001) and Levin (1991) did. The latter two afore-mentioned authors unfortunately did not provide a quantitative analysis of the individual random errors. These individual errors remain unaffected, of course. Tan and Johnson (1990) divided the test persons into classes resulting in a class of test persons with thresholds even lower than 40 μA. However, they did not test for blemish data (blank test). That the method described by Tan and Johnson (1990) could possibly be bordered also by a threshold of 0 μA (threshold class) which is evidently absurd. In particular, it is not possible to test the assertion whether individual persons are considerably more sensitive with respect to power perception than all persons.

Adaptation measurement procedure

If an adaptation on the non-adequate stimulus exists, the perception of a current can be masked by a preceding stronger, "masking" current. The strengths of the masking signals used are listed in Table 4.

In the case of a subliminal masking signal I_M=100 μA (rms), the average values of the threshold current values show no significant differences compared to the measurements without a masking signal trial. Differences were found in the measurements using a good observable first signal (masking signal) of 500 μA (rms) for test persons A and B, and 300 μA (rms) for test person C. To level off the different reference levels, the changing of the thresholds is given as the relative variation of the threshold between the measurements with and without masking signal in Fig.6.

It was found that the relative threshold of all test

Table 4 Parameters of the adaptation measurements. Listed data are the parameters of experimental setup in the case of determinating the adaptation at non-adequate irritation

Test person	Sex	$I_{M,1}$ / μA	$I_{M,2}$ / μA	t_P / s	t_T / s	ΔI / μA	N
A	M	100	500	2	1	5	5
B	M	100	500	2	1	5	5
C	F	100	300	2	1	5	5

$I_{M,1}$: Amperage of the masking, not noticeable signal trial; $I_{M,2}$: Amperage of the masking, well noticeable signal trial; t_P: No-pulse period time; t_T: Test time; ΔI: Increment of the test amperage; N: Number of the iterations

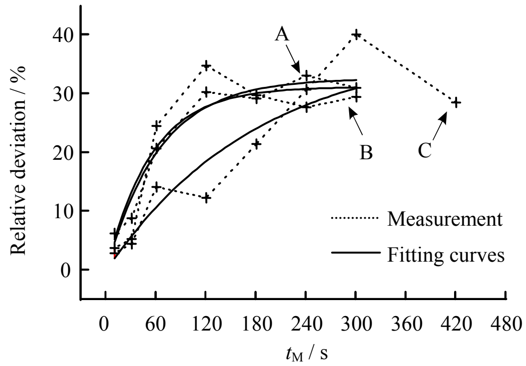


Fig.6 Relative change of thresholds due to adaptation effects. Measurement points are connected by dotted lines; the curves are described by Eq.(2). Test person C received a smaller masking current than candidates A and B

persons increases with longer lasting masking signal time t_M, which can be described by the exponential formulation

$$A_1[1-\exp(-t_M/t_1)]. \quad (2)$$

A constant term can be neglected, since the relative deviation has to be 0 at t_M=0. The time constant t_1 is about 1 min for the test persons A and B, and about 3 min for C (Table 5).

Table 5 Results of the adaptation measurements. Listed data are the parameters approximating the relative current threshold change depending on the duration of the masking signal

Test person	A_1 / 1	t_1 / s	R^2 / 1
A	0.327±0.017	63.1±10.9	0.96352
B	0.312±0.034	53.9±21.3	0.84945
C	0.383±0.095	180.7±95.6	0.84770

These differences may be due to the different amperages of the masking signal, as the time constant t_1 may depend on the amperage I_M. Factor A_1 shows no dependence on I_M, so the final adaptation level is constant.

This means the strength of adaptation depends on the preceding signals. Depending on the absolute threshold, this influence cannot be neglected. So, how long does one have to wait before a new trial can be started? This question is answered by the experiments varying the pause time t_P, shown in Fig.7. The functional approximation is

$$I_S(t_P)=I_0+A_1e^{-t_P/t_1}+A_2e^{-t_P/t_2}, \quad (3)$$

resulting in the parameters given in Table 6; the calculated curves can be found in Fig.7 as well. The time constants t_1 and t_2 are unacceptably high: to be sure that one signal trial is not affected by the preceding trials, one would have to wait for minutes. This procedure is not practicable, since several hundreds of trials are necessary.

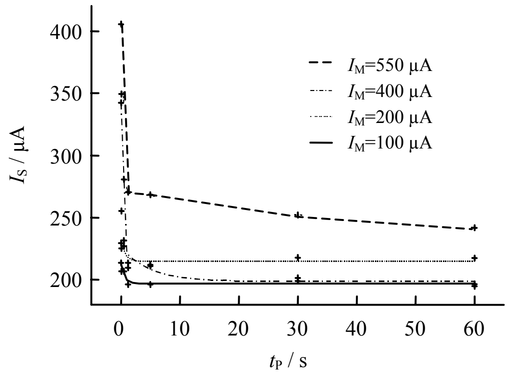


Fig.7 Dependency of the current threshold I_S on the pause time t_P for masking signals of different amperages I_M

Confidence rating procedure

The results for the current threshold of the ECSs following the classical methods is not satisfactory: the existence of an adaptation on the non-adequate stimulus leads to an increase of the current threshold using classical test strategies, but we are looking for the resting threshold.

The preceding determinations of the current threshold have to be critically reviewed as these statistical approaches were counterproductive.

Altogether 11 test persons took part in this test, but 4 of them quit before completing it because of the high time burden. The examination extended over several sessions, typically two weeks long. All test persons stated after the examination that felt physically weakened due to the concentration. The subjective threshold of one test person was close to the maximum power of the current source, so no signals far above the threshold could be generated which are needed for extrapolation to the stimulus limen. Thus, this test person had to be excluded as well.

According to the five rating classes, probabilities at four different criteria for each amperage can be calculated. Less points were determined, if a rating class was not filled. This happened in the following items:

Table 6 Results of the adaptation measurements. Listed data are the parameters approximating the current threshold course depending on the pause time [Eq.(3)]

I_M / μA	I_0 / μA	A_1 / μA	t_1 / s	A_2 / μA	t_2 / s	R^2 / 1
100	196.99±1.65	15.24±2.80	0.612±0.315	−	−	0.88218
200	214.91±2.46	14.23±4.08	0.756±0.598	−	−	0.75538
400	198.64±7.32	116.01±15.39	0.073±0.024	27.65±13.09	4.878±6.401	0.98678
550	230.66±4.79	133.37±0.89	0.185±0.004	41.24±4.56	46.244±9.881	0.99995

I_M: Amperage of the masking signal; R^2: Coefficient of determination; All other parameters: See Eq.(3) (standard errors are given)

1. If a high amperage (=good perceptible stimulus) was applied, there were no false alarms in rating class "5" (p(yes|N) = 0);

2. One (here: the middle) rating class was not used by one test person (the answer "3" was never given).

The test persons had to answer N_{SN} trials containing a signal (a stimulus current) and N_N trials without a signal. Altogether the test person had to answer $N_{SN}+N_N$=200 questions, resulting in $n_{SN,a}$ answers a (a=1, …, 5) if a signal existed and $n_{N,a}$ if not.

The idea of the confidence rating procedure is to make a separate evaluation for each criterion as if the whole test procedure was a yes/no-task with this one criterion. For that the probabilities $p(a|\cdot)$ are added to the probabilities below the actual criterion of answering "yes" with a signal, p(yes|SN), and without a signal, p(yes|N), respectively (Sorkin, 1999; Stanislaw and Todorov, 1999).

Now the probabilities can be sketched down in pairs [p(yes|SN); p(yes|N)] as a so-called receiver operating curve (ROC) diagram for each tested amperage. Lower stimulus strengths yielded ROC curves closer to the quadrant bisect, a straight line with a rise 1 would mean that the test person could not distinguish between a signal and a missing signal.

Using the inverse transformation Φ^{-1} of the cumulative normal distribution

$$\Phi(x;\mu,\sigma)=\frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{x} e^{-\frac{(u-\mu)^2}{2\sigma^2}}\,du\,, \qquad (4)$$

these probabilities are transformed into z-scores (x: variable, μ: mean, σ: standard deviation). They are linearly fitted using

$$\Phi^{-1}[p(\text{yes}|\text{SN})] = s\cdot\Phi^{-1}[p(\text{yes}|\text{N})] + d'\,. \qquad (5)$$

The d' extracted from this specifies how "good" the test person could observe signal trials of the stimulus intensity I namely independent of the subjective assessment. Evaluation now is done by drawing the measure of detectability d' against the amperage I. The values for d' decrease down to 0 before reaching I=0, which can be seen in Fig.8.

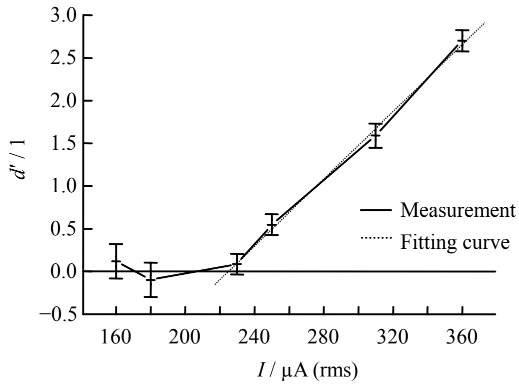


Fig.8 The evaluation of the delectability d' for different stimulus amperages from the ROC diagrams yields the upper limit of the amperage with which the test person cannot detect a current flow

This detectability limit is called the stimulus limen I_{SL}. Above this value, d' increases linearly with I:

$$d'(I)=\begin{cases} d'=0, & I\le I_{SL}; \\ d'=a\cdot I+b, & I>I_{SL}. \end{cases} \qquad (6)$$

Measuring d' for $I>I_{SL}$ allows extrapolation of the value of I_{SL}, which was used in the following measurements. This means, that measurements were made using amperages where the test person always could easily indicate a signal, but afterwards it is possible to tell below which amperage he/she could not register a signal. With the other five test persons, one refrained from making the ROC curves individually. The Figs.9a~9e are the plots of the measured delectability d' against the stimulus intensity I for the

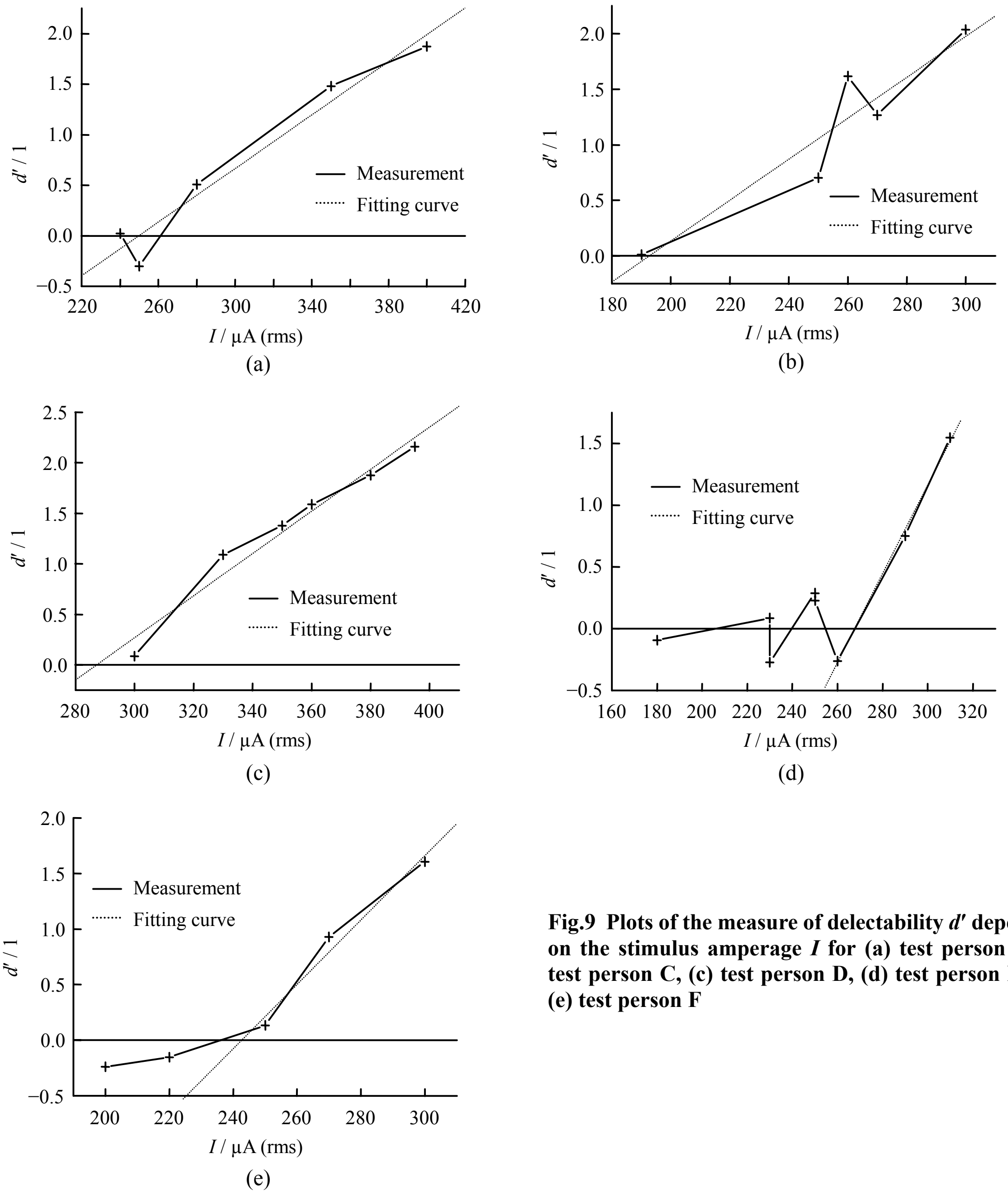


Fig.9 Plots of the measure of delectability *d′* depending on the stimulus amperage *I* for (a) test person B, (b) test person C, (c) test person D, (d) test person E, and (e) test person F

other participants.

The parameters for Eq.(6) are determined from these measurements, in particular the amperage of the stimulus current, can be found in Table 7. The coefficients of correlation show that the curvature can be described by the given function.

Consequently, the perception threshold of a 50 Hz current for the described experimental setup is about 200 μA. All determined values did not show large deviation. The underlying dispersion is certainly right skewed (since e.g. negative values cannot occur), however, a normal distribution should be accepted for the calculation.

With the average of 244.17 μA and standard deviation 33.02 μA, a lower limit of the 95% range of 179.45 μA was found. This lower limit should be used as a worst case estimation.

Looking at the values of moist skin (Table 8, Fig.10), it surprisingly turns out that the values do not differ significantly for test persons B and F from those with dry skin. Only in the case of test person D, could a small increase be listed although a drop was

Table 7 Results of confidence rating procedure. Amperage of the stimulus limen and other parameters resulting at SDT method in dry skin

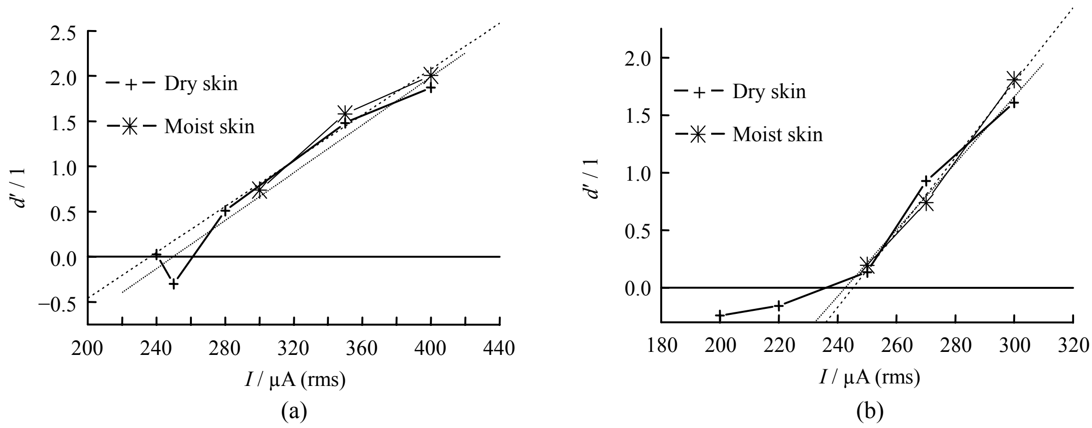
Test person	Sex	a / μA^{-1}	b / 1	R / 1	I_{SL} / μA (rms)
A	F	0.01967±0.00075	−4.43±0.22	0.99854	225.0
B	F	0.01325±0.00171	−3.31±0.53	0.97603	249.8
C	M	0.01841±0.00389	−3.55±0.99	0.93908	192.7
D	M	0.02085±0.00199	−5.99±0.71	0.98221	287.1
E	F	0.03596±0.00162	−9.63±0.46	0.99899	267.8
F	M	0.02892±0.00466	−7.02±1.28	0.98728	242.6

R: Measure of determination

Table 8 Results of confidence rating procedure. Amperage of the stimulus limen and other parameters resulting at SDT method in moist skin

Test person	Sex	a / μA^{-1}	b / 1	R / 1	I_{SL} / μA (rms)
B	F	0.01268±0.00240	−2.99±0.84	0.98261	236.2
D	M	0.02270±0.00152	−7.60±0.61	0.99777	335.0
F	M	0.03250±0.00229	−7.97±0.63	0.99753	245.2

R: Measure of determination



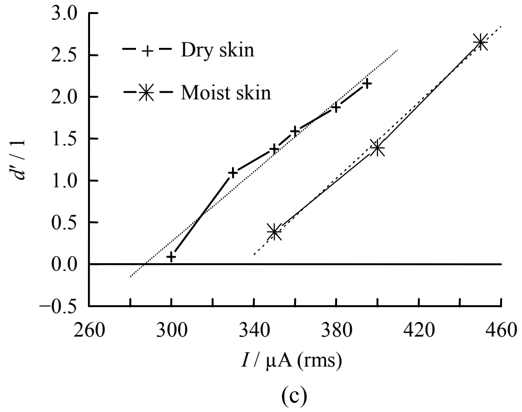


Fig.10 Plot of the measure of detectability *d′* depending on the stimulus amperage *I*. The stimulus limen for dry skin (measurement points with dotted extrapolation line) and moist skin (measurement points with dashed extrapolation line) match. (a) Plots for test person B; (b) Plots for test person D; (c) Plots for test person F. In contrast to the preceding test persons, there is an increase of the amperage of the Stimulus limen for moist skin

expected. Moistening of the skin obviously leads to a decreasing of the electrode skin contact resistance; with this the decrease of the voltage thresholds can be explained in particular but it does not change the amperage of the stimulus limen I_{SL}.

The change of the current threshold found using the classical methods has to be attributed to a changing of assessment by the test person, e.g. due to the strange feeling of cold.

DISCUSSION

Since the experimental setup and the measurement situation will influence the current threshold, it is problematic to compare the results of different authors.

Dalziel and Mansfield (1950) were one of the first to determine systematically the current threshold of so-called "leakage current" in everyday situations.

He asked the test persons to hold devices like a lamp or an electric drill in the hand and to announce the first occurrence of a perception. Due to these experimental conditions, the current introducing area is relatively large (nearly hand palm size) and not well determined. He consequently reported the highest current threshold values which were about one order of magnitude higher than our result.

Tursky and O'Connell (1972) used concentric electrodes. Increasing the test current by 0.1 mA steps until first perception, he used a kind of direct adjustment by the test person. But the pause time of 20 s between the 1 s lasting signals is too short to prevent adaptation, so his relatively high current thresholds of 330 μA to 440 μA at 60 Hz may be partly caused by an adaptation, aside from the fact that he attached the electrodes to the forearm.

Levin (1991) placed the active electrode on the finger like we did, but he placed this electrode at the underside of the wrist, thinking that the stratum corneum is thinner there compared to the fingertip. He found a wide range of threshold values, ranging from 51 μA (rms) to 715 μA (rms) at 60 Hz. Eighty percent of his test persons had a threshold higher than 200 μA. This can be explained by the greater electrode area on the one hand (he used a 2 cm×1 cm surface electrode) and by the lower innervation density compared to the highly sensitive fingertip on the other hand.

None of the authors mentioned above considered a possible effect of adaptation on the non-adequate effect. The question whether the skin receptors adapt to the non-adequate stimulus or not, is of central importance: because without this knowledge, either too high thresholds or obviously within given time variable thresholds are measured with the classical methods (depending on the used technique). All the more surprising is that none of the previous examinations dealt with this question. Dalziel (1954) mentioned that it was easier for the test persons to recognize a stimulus when increasing the test current the first time, while it was difficult to gain this value once again—a clear indication of an adaptation process, but he did not pursue this question further.

Adaptation: We found that, as in the case of a mechanical stimulus, the skin receptors adapt to the electrical stimulus. Therefore, strong stimuli can hide a subsequent weak stimulus. In an everyday life situation, as we must take them as a basis for our safety considerations, the person did not come in contact with electricity (for a long time), so he/she is not adapted to the non-adequate stimulus. However, all classical methods (like the popular method of constant stimuli) determine the threshold with a sequence of different amperages, so that an adaptation will set in and a quantitative analysis of the desired resting current threshold is impossible.

In spite of this restriction of the classical methods, which are used up to now, there would exist a possibility to measure a resting current threshold: After every test signal trial, one must wait until the adaptation has faded away. However, this would lead to impracticably long measuring sessions following the found time constants.

Individual rating factors: We could further show that an active individual interference like “reacting as sensitively as possible” changes the perception clearly, but not reproducibly.

This tallies with the results of Tursky and O'Connell (1972) who found that there is only low to moderate reliability of the threshold level. In spite of that, he found an excellent reliability at all suprathreshold levels, like the limit of discomfort and pain. We think that these findings were due to the fact that the subjective threshold varies with the subjective variables mentioned above. So it is not surprising that he found a minor day-to-day reliability.

Levin (1991) used the direct adjustment method. His lower limit of 51 μA is fairly small; in fact, his method could not prevent a finding of a limit of 0, since this method does not include any control of the test person like blind trials. It is obvious that such a result would not make sense.

Abandoning the classical methods, we used the signal detection theory which was originally developed to describe adequate stimuli. By extrapolating the detectability d' to zero, we determined an amperage, below which a change of perception it is not to be expected. This value is below the values found by means of classical methods. In contrast to Tursky’s day-today variations, the stimulus limen (or the dependence of detectability on the amperage) remains the same during our investigation using the confidence interval method.

By means of the stimulus limen (from signal detection theory method) which are independent of subjective parameters, we cannot confirm that women have a higher sensibility than men towards electrical currents although this assertion must be limited on account of the small size of the examined group. In fact, the "most sensitive" person here is a man with approx. 193 μA. No sex specific difference can be recognized equally by means of the slope, which is 0.02 μA^{-1} on the average. In summary, no sex specific dependence could be found.

Anatomical factors: If the everyday life habits listed in Table 9 are considered we can set up a connection between the mechanical load of the skin during work and leisure activities. Persons with a thicker skin callus, caused by mechanical strain during work or hobby activities, show higher values.

Table 9 Habits of the test persons following the questionnaire. High values of I_{SL} correlate to high mechanical exertion of the skin

Test person	Sex	I_{SL} / μA (rms)	m. occupation	Sport
A	F	225.0	■□□□□	■□□□□
B	F	249.8	□□□□□	■■■□□
C	M	192.7	□□□□□	□□□□□
D	M	287.1	■■■■■	■■■■■
E	F	267.8	□□□□□	■■■■□
F	M	242.6	□□□□□	■■■□□

m. occupation, sport: Rating on a 5 point scale of the own manual occupation during work and during leisure-time activities

It is well-known that mechanical load forces the development of structural fat and so the epidermis thickens, therefore the current threshold increases. The difference found by Irnich and Batz (1989) can be traced back to skin anatomy. Therefore, an expected influence of anatomical factors appears. This influence cannot be leveled out by a suitable measure method: it is due to the fact that the amperage is an "outer" measurand while the stimulated receptors react on an "inner" variable, the electrical field which develops inside the tissue.

The determined value at 50 Hz power net frequency is 179 μA. This is by far lower than the 500 μA provided by the German regulation. Currents of this strength may already trigger pain reactions at the described experimental setup with some test persons. Canadian and USA regulations only allow an amperage of 100 μA here and provide better protection.

CONCLUSION

The limitation of leakage currents is an easily checkable safety guideline. Previous examinations neglected the influence of adaptation effects and of the individual assessment.

The confidence rating procedure of the signal detection theory overcomes these limitations and provides a limit independent of adaptation and individual assessment factors. Based on these measurements, we recommend a clear sharpening of the previously established safety guidelines.

References

Dalziel, C.F., 1954. The threshold of perception currents. *AIEE Trans. Power Apparatus Syst.*, **73**:990-996.

Dalziel, C.F., Mansfield, T.H., 1950. Effect of frequency on perception currents. *AIEE Trans.*, **69**:1162-1168.

Gescheider, G.A., 1976. Psychophysics: Method and Theory. Lawrence Erlbaum Associates, Hillsdale, New Jersey.

Irnich, W., Batz, L., 1989. The perception threshold for 50 Hz alternating voltage and current. *Biomed. Tech. (Berl.)*, **34**(9):207-209.

Johansson, R.S., Vallbo, A.B., 1979. Tactile sensibility in the human hand: relative and absolute densities of four types of mechanoreceptive units in glabrous skin. *J. Physiol. (Lond)*, **286**:283-300.

Kaczmarek, K.A., Webster, J.G., Bach-y-Rita, P., Tompkins, W.J., 1991. Electrotactile and vibrotactile displays for sensory substitution systems. *IEEE Trans. Biomed. Eng.*, **38**(1):1-16. [doi:10.1109/10.68204]

Leitgeb, N., Schröttner, J., 2001. Risk from electric current greater than assumed. *Biomed. Tech. (Berl.)*, **46**(11): 307-310 (in German).

Levin, M., 1991. Perception of chassis leakage current. *Biomed. Instrum. Technol.*, **25**(2):135-140.

Macmillan, N.A., Creelman, C.D., 1991. Detection Theory. Cambridge University Press, Cambridge.

Patino, J., Korneluk, J.E., Tracy, J.L., 2006. Apparatus and Method for Stimulating One or More Areas on a Wearer. United States Patent Application 20060084480.

Schmidt, R.F., Thews, G., 1995. Physiologie des Menschen, 26th Ed. Springer, Heidelberg.

Sorkin, R.D., 1999. Spreadsheet signal detection. *Behav. Res. Methods Instrum. Comput.*, **31**(1):46-54.

Southwood, W.F.W., 1955. The thickness of the skin. *Plast. Reconstr. Surg.*, **15**(1):423-429. [doi:10.1097/00006534-195505000-00006]

Stanislaw, H., Todorov, N., 1999. Calculation of signal detection theory measures. *Behav. Res. Methods Instrum. Comput.*, **31**(1):137-149.

Tan, K.S., Johnson, D.L., 1990. Threshold of sensation for 60-Hz leakage current: results of a survey. *Biomed. Instrum. Technol.*, **24**(3):207-211.

Tursky, B., O'Connell, D., 1972. Reliability and interjudgment predictability of subjective judgments of electrocutaneous stimulation. *Psychophysiology*, **9**(3):290-295.

Vallbo, A.B., Johansson, R.S., 1984. Properties of cutaneous mechanoreceptors in the human hand related to touch sensation. *Hum. Neurobiol.*, **3**(1):3-14.

Whitton, J.T., 1973. New values for epidermal thickness and their importance. *Health Phys.*, **24**(1):1-8.

Whitton, J.T., Everall, J.D., 1973. The thickness of the epidermis. *Br. J. Dermatol.*, **89**(5):467-476. [doi:10.1111/j.1365-2133.1973.tb03007.x]