Med. & Biol. Eng. & Comput., 1983, 21, 750-755

Impedance measurement of individual skin surface electrodes

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Abstract—*The methods for the individual determination of skin surface electrode impedances are briefly discussed. A measurement technique is described with which it is possible to measure two skin surface electrodes simultaneously, but individually, at the same frequency. The design of a small, portable, battery-operated meter using this principle is described with block diagrams. Results are presented from the study of bilateral g.s.r. waves, the site dependence of the skin impedance, the differences between 10 Hz and 1000 Hz data, and tissue segment impedance.*

Keywords—*Galvanic skin response (g.s.r.), Impedance meter, Skin impedance*

1 Introduction

THIS paper is concerned with the impedance measurement of skin surface electrodes, and the feasibility of determining the impedance of each electrode. A small, portable electrode impedance meter capable of taking measurements from two skin surface electrodes simultaneously, but individually, at the same frequency, is presented.

The electrode-skin impedance is an important noise-determining parameter, e.g. in e.c.g. systems, both with respect to motion artefacts (GORDON, 1975; BURBANK and WEBSTER, 1978), and 50/60 Hz interference (HUHTA and WEBSTER, 1973). Such interference is determined not only by the impedance level, but also by the impedance balance (symmetry). This is one of the reasons why individual measurement of electrodes is necessary. Skin surface electrode impedance often varies in an unpredictable way, and not necessarily as a function of the electrode proper, but owing to physiological changes in the test subject. The simultaneous measurement of two electrodes is therefore the most effective and reliable way of comparing different electrode models, comparing different skin sites as well as application procedures. Simultaneous measurement is also a prerequisite for bilateral g.s.r. studies (YAMAMOTO *et al.*, 1978).

2 Measurement principles

Given two skin surface electrodes, their individual impedances cannot be determined without introducing a third electrode, the reference electrode. The reference electrode can be used in several ways.

2.1 *With a two-terminal impedance measuring device*

The impedance of the third electrode may be so low that its contribution is negligible. Each electrode can then be measured with respect to the reference electrode (monopolar system)*. If this is not the case, the complex impedance can be measured between all three electrodes (three measurements), and a delta-wye transformation calculated (OLSON *et al.*, 1979). This is the oldest method for individual electrode impedance determination. HORTON and RAVENSWAAY (1935) introduced it with calculations from six complex impedance values obtained with four electrodes.

A two-terminal measuring device can consist of a signal source and an a.c. voltmeter, possibly with a phase-meter, or an oscilloscope (PLUTCHIK and HIRSCH, 1963); a two-terminal bridge (LAWLER *et al.* 1960); a lock-in amplifier (YAMAMOTO and YAMAMOTO, 1979; GRIMNES, 1982*a*); a transient method (TREGEAR, 1966, POON and CHOY, 1978); a spectrum analyser and a noise signal generator; by measurement of signal changes when the unknown impedance is loaded with known impedances, often using the physiological signal of interest as the signal source (GEDDES and BAKER, 1966; MÖRKRID *et al.*, 1980).

2.2 *With a three-terminal impedance measuring device*

Bridges or a.c. potentiometers capable of both three- and four-terminal measurements have frequently been used. The method was pioneered by HORTON and

**Actually this is a pseudo-method, because the reference electrode impedance should be measured to confirm that it is negligible*

First received 3rd February and in final form 28th March 1983

RAVENSWAAY (1935), and refined by BARNETT (1938). A simplified version illustrating the principle is shown in Fig. 1. Three electrodes are positioned on the skin surface, and the skin is supposed to have a large impedance relative to the better conducting deeper layers. The two resistors r must be large enough to secure a constant current condition in the two bridge arms. When the impedance of the C_p and G combination is equal to the impedance of the measuring electrode M, the bridge is balanced. As long as the current through resistor r is constant, the impedance of electrode C does not intervene, and at balance there is no current flow through the reference electrode.

An operational amplifier can be used to convert a two-terminal device to a three-terminal one. Fig. 2 shows the principle with a constant potential source and a constant current source.

3 Measurement technique

Fig. 3 shows the measurement technique; it is a variety of the constant current circuit shown in Fig. 2. In Fig. 3*a* the amplifier A2 has a differential input, the other amplifier has a single-ended input, and the current source is nonfloating. In Fig. 3*b* the current

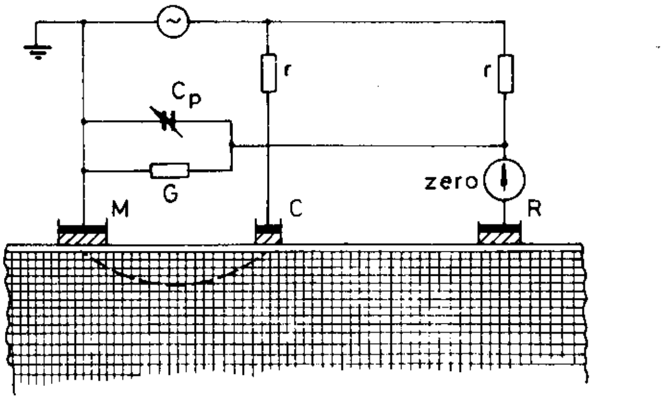

Fig. 1 *Conventional three-terminal bridge circuit connected to three skin surface electrodes. M is the measuring electrode, C the current-carrying counter electrode and R the reference electrode*

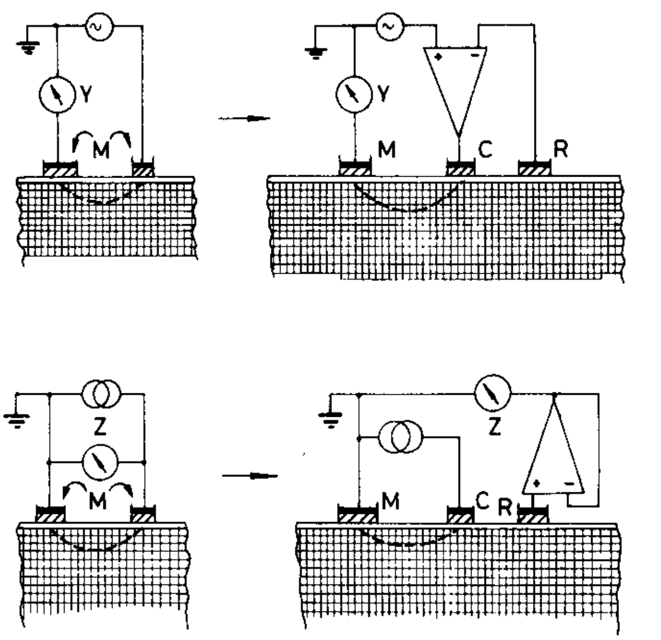

Fig. 2 *Operational amplifiers converting two-electrode measuring circuits to three-electrode circuits. Left: measuring sum of two electrodes, right: measuring single electrode. Above: constant potential circuits, outputs proportional to admittance (Y), below: constant current circuits, outputs proportional to impedance (Z)*

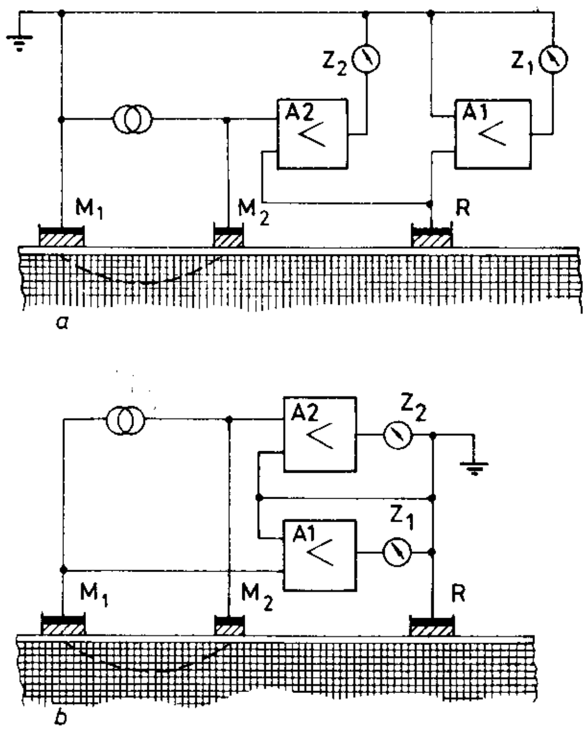

Fig. 3 *New method for simultaneous individual measurement of two electrodes. Due to the use of constant current sources, outputs are proportional to impedances of M_1 and M_2: (a) with one amplifier (A2) with differential input; (b) both amplifiers with single-ended inputs, floating current source*

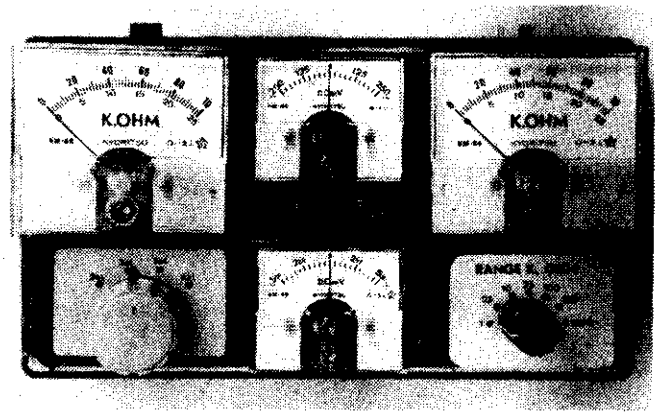

Fig. 4 *The instrument*

source is floating, and both amplifier inputs are single-ended. The potential difference between the measuring electrodes M_1 and M_2 and the reference electrode R is proportional to the impedance of M_1 and M_2, respectively. The reference electrode R is not current carrying and therefore not critical.

A similar simple variety of the constant potential circuit of Fig. 2 does not exist. The instrument to be described is based on the circuit of Fig. 3*b*.

instrument also effective for high-impedance systems susceptible to a large amount of noise pick-up, twin-*T* notch filters were added, giving about 40 dB rejection of power line fundamental frequency interference. After additional a.c. amplification (gain $\approx$ 40), the signals are rectified in averaging circuits and displayed on the moving coil meters. Full scale deflection corresponds to about 1 mV a.c. at the input. The measurement technique does not necessitate

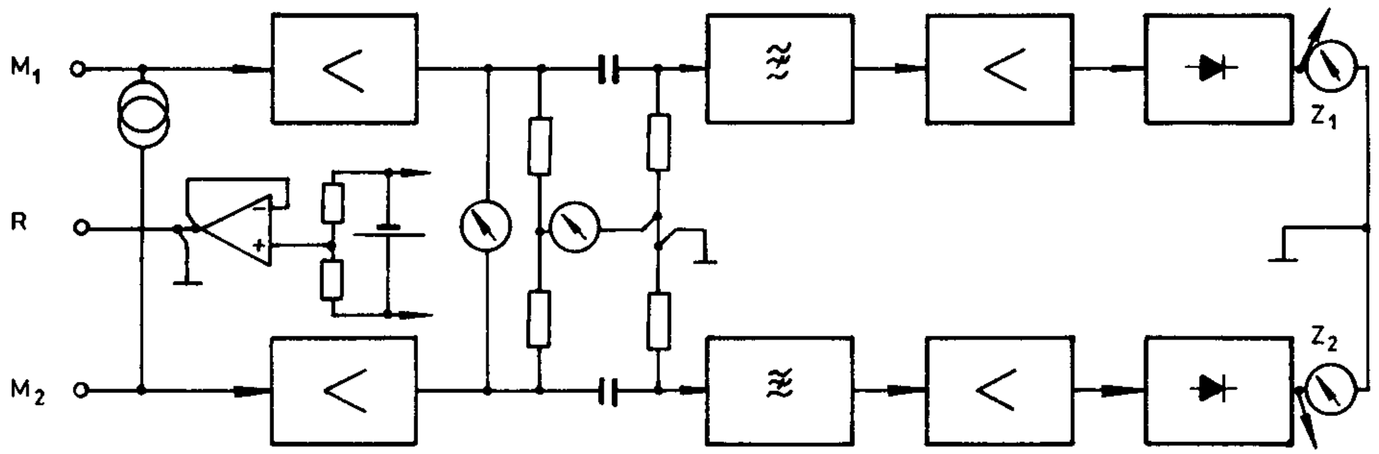

Fig. 5 *Block diagram of instrument*

4 Constructional details

A small, battery-operated electrode impedance meter has been built on the basis of the principle shown in Fig. 3*b*. Fig. 4 shows the instrument and Fig. 5 the block diagram. In addition to the two impedance-displaying meters, two smaller d.c. meters have been added to check the d.c. potentials between the measuring electrodes, and between these two and the reference electrode. The instrument has two separate batteries, one for the constant current source with the oscillator (Fig. 6), and one for the measuring circuits (Fig. 5).

The input amplifiers (Fig. 5), gain $\approx$ 3, 3, are d.c. coupled owing to the d.c. meters. To make the

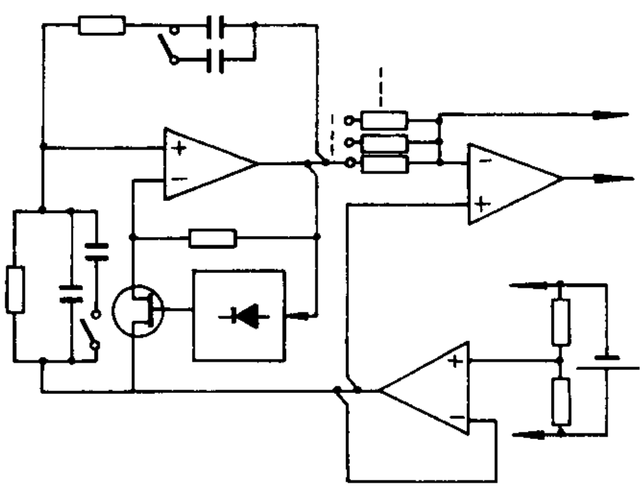

Fig. 6 *Block diagram of constant current source with oscillator. Switches for the choice between* 10 *Hz or* 1000 *Hz operation, and constant current level*

measurement of complex impedance values, and no synchronous rectifiers were used. The instrument therefore displays the magnitudes (moduli) of the impedances only, according to the first method mentioned in the second part of Section 2.1.

The oscillator is a Wien-bridge circuit with amplitude control feedback for a stable, pure sinusoidal signal. The output is taken from an operational amplifier constant-current circuit (Fig. 6). The current levels are determined by the choice of input resistor to this circuit. Seven fixed current levels between 1 μA and 1 nA correspond with the seven full scale values in the range 1 kΩ to 1 MΩ. The oscillator has a switch for the choice of 10 Hz or 1000 Hz operation.

The instrument has been equipped with a switch for the choice of two-, three-, or four-electrode measurement modes, the corresponding input circuits are shown in Fig. 7. The four-electrode mode is used

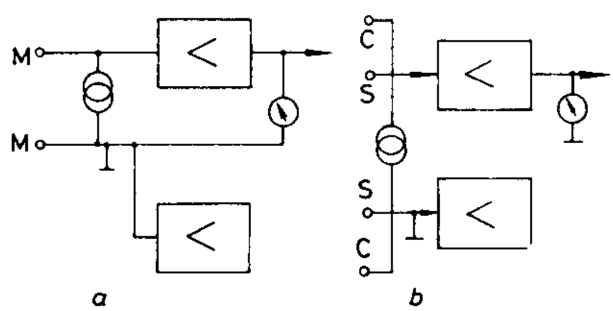

Fig. 7 *Input circuits for* (*a*) *two-electrode measuring mode and* (*b*) *four-electrode measuring mode. S are segment-determining electrodes*

for tissue segment impedance measurement. A segment of an arm, for example, can be measured, without the intervention of skin impedance.

5 Results

Three instruments have been built. First the instruments were d.c. calibrated by trimming the d.c. amplifier gains. The notch filters were adjusted to 50 Hz, and the impedance values were calibrated using three Y-coupled precision resistors, and the gain of the two a.c. amplifiers adjusted. One of the Y-resistors was changed from zero to its full scale reading, and the complete independence of the other meter reading was controlled. Then two pre-gelled e.c.g. electrodes were attached to the forearm, and a third electrode was brought in variable contact with the same forearm. No changes were noticeable in the fixed electrode reading when the other was varied from a very low reading to more than full scale. This result was obtained both at 10 Hz and 1000 Hz.

Two pre-gelled e.c.g. electrodes were positioned on the thenar of the left and right hand palms, and a galvanic skin response (g.s.r.) was elicited with a needle prick on the dorsal side of the hand, first on the right, then on the left. The third g.s.r. wave was elicited by a deep breath. The result is shown in the upper two traces of Fig. 8. The identical results show that the g.s.r. waves are not local responses, but come from more central parts of the sympathetic nervous system. A comparison between palmar and nonpalmar sites is shown in the two lower traces of Fig. 8. The forearm completely lacked a g.s.r. It has earlier been shown (GRIMNES, 1982*a*), that nonpalmar sites may or may not be g.s.r. sensitive.

With one electrode on the heel and the other on the palm (Fig. 9), the curves are no longer identical. The first wave is due to a prick on the foot, the second to a deep breath, and the third to a prick on the hand. Again the response was not local, even when the prick was applied at the *foot* the response was first seen from the *palm*; the heel response was delayed by about one second.

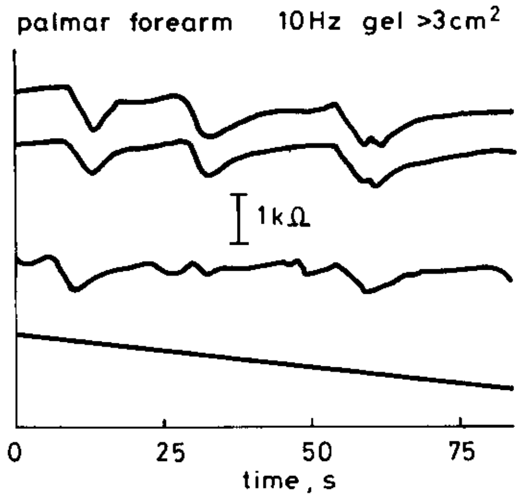

Fig. 8 *Bilateral g.s.r. waves. Two upper curves: left and right hand palms. Two lower curves: palmar and forearm electrodes, same arm. Impedance level for all four curves approximately* 15 kΩ

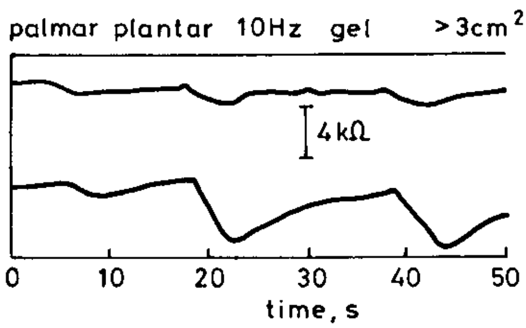

Fig. 9 *Bilateral g.s.r. waves, palmar and plantar (lower curve) electrodes. Impedance level palmar approximately* 15 kΩ, *plantar approximately* 40 kΩ

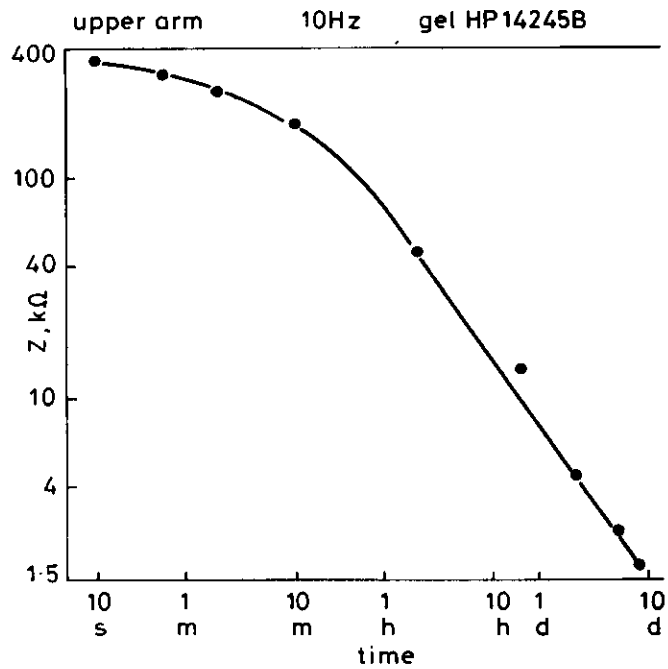

Fig. 10 *Long-term impedance of pre-gelled e.c.g. electrode*

Fig. 10 shows the long-term result with a pre-gelled e.c.g. electrode. By inspection and capacitance measurement (GRIMNES 1982*b*), it is possible to show that one part of this impedance reduction is due to electrolyte spread and increased effective electrode area, e.e.a. (skin area wetted by electrolyte), and the other part is due to electrolyte penetration into the skin. The e.c.g. electrode used was so constructed that the contact paste was contained in a stiff plastic cup. Because of the stiff construction the paste could not be directly squeezed out, but as a long-term effect the electrolyte slowly spread on the skin surface. Also the drying-out process was slow because of the tight cup and the slow spread. With some models of electrode the impedance curve passes through a minimum after some hours or days due to a drying-out process.

Fig. 10 indicates a defined *initial* skin impedance before the electrolyte spread and skin penetration have started. The initial value is a function of the skin site, but also of sweat duct filling. The initial impedance is therefore not a direct measure of the skin properties proper, but values relative to other skin sites, as shown in Table 1, may reflect basic and stable skin properties.

Table 1. Site dependence of skin impedance. Initial values of skin impedance Z, together with control impedance $Z_{control}$. Z given in $k\Omega\,cm^2$, and measured with a $12\,cm^2$ electrode plate placed directly on the skin just after a short breath had been applied to the skin to increase skin surface conductivity. $Z_{control}$, in $k\Omega$, is the impedance of a pre-gelled e.c.g. electrode fixed to the forearm. Three measuring series at two-hour intervals

	$k\Omega\,cm^2/k\Omega$		
Hand—dorsal side	720/80	210/17·5	300/33
Forearm —ventral—distal	250/80	240/17·5	190/35
Forearm —ventral—middle	840/80	230/17·5	360/36
Forearm —ventral—proximal	560/80	180/17·5	260/36
Upper arm—dorsal	840/75	260/16	660/36
Upper arm—ventral	1000/70	300/16	780/34
Forehead	60/70	36/16	48/35
Calf	325/45	375/17	325/36
Thorax	130/37	110/16	130/35
Palm	200/80	150/17·5	200/33
Heel	120/60	180/15	120/35

Table 1 shows the site dependence of the skin impedance. An electrode fixed to the forearm served as the control. The measuring electrode was a large plate of area $12\,cm^2$, in order to obtain average values. Even with this electrode a considerable spread was found, particularly on thoracic sites. The electrode plate was used without conductive gel/paste. It was found that by applying a short breath to the skin just before positioning the electrode, surprisingly stable values were obtained from the beginning. These values presumably correspond with the initial value shown in Fig. 10.

Table 2. Initial impedance at 10 Hz and 1000 Hz, measured with a $1\,cm^2$ plate electrode after breath application. Values in $k\Omega\,cm^2$

	$k\Omega\,cm^2$ 10 Hz	$k\Omega\,cm^2$ 1000 Hz
Hand—dorsal side	320	31
Forearm—ventral side	550	29
Upper arm—dorsal side	700	33
Forehead	40	7
Calf	650	28
Thorax	600	16
Palm	190	25
Heel	500	25

The first column (left) of Table 1 shows a large variation in the control impedance, reflecting unstable sweat duct filling during measurement. The Z values cannot therefore directly be compared. The two other columns show stable results at two different levels of control. According to Fig. 10 the control electrode impedance will also change, and the values are mostly a control of the variations during one measuring series (approximately 5 min). Table 1 does not confirm our assumption that the impedance varies in a parallel fashion at different skin sites, e.g. palmar/plantar sites, the distal part of forearm, calf and thorax. The other sites show a correlation, but not in a very uniform way. Note that the forehead represents a remarkable low-impedance skin site.

Table 2 shows the difference between the 10 Hz and 1000 Hz results. A smaller electrode, $1\,cm^2$, was chosen to prevent such small 1000 Hz impedance values that the series impedance of deeper skin layers and tissue segments became significant. Examples of tissue segment impedances are shown in Table 3. These values are not very dependent on the measuring frequency, and they are of importance, e.g. in surgical diathermy, because they determine the voltage drop along a current path.

Table 3. Tissue segment impedance, 10 Hz and 1000 Hz. Adult test subject

	Ω
Upper arm and forearm	350
Sternum—middle upper arm	150
Finger	500
Leg	500
Sternum—middle calf	200
Sternum—middle thigh	50

The electrode polarisation impedance is usually less than $1000\,\Omega\,cm^2$ (10 Hz) (GRIMNES, 1982; SWANSON and WEBSTER, 1974). The impedance of the contact electrolyte is usually less than $100\,\Omega$, (SWANSON and WEBSTER, 1974), and the tissue segment impedance usually less than $1000\,\Omega$ (Table 3). From Table 1 it is therefore evident that when measuring an impedance in excess of $100\,k\Omega\,cm^2$, the skin impedance is the dominating part. In this paper M has therefore been called the measuring electrode, and not the measured electrode. Electrode polarisation impedance may intervene appreciably only if the plate-wetted area is much less than the skin-wetted area (e.e.a.). Tissue segment impedance may intervene appreciably only if the measured values are low, either because of a high measuring frequency, or large e.e.a. The expression 'impedance of a skin surface electrode' therefore usually does not mean the impedance of the electrode proper, but the impedance of the skin wetted by the contact electrolyte.

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