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Instantaneous measurement of electrical parameters in a palm during electrodermal activity

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Instantaneous Measurement of Electrical Parameters in a Palm During Electrodermal Activity

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Abstract—**The determination of impedance can be performed by means of a frequency-domain analysis or a time-domain analysis. The latter has the advantage of being able to measure instantaneously all the frequency characteristics of impedance. The method is hence well suited to obtain the biological impedance which changes with time. An instantaneous method of measuring skin impedance, by using time-domain analysis has thus been developed. The fast Fourier transform (FFT) of the step response for current to the skin can determine the palm impedance. This method can carry out the determination of the parameters of the palm skin impedance during a galvanic skin reflex (GSR), which is impossible by means of frequency-domain analysis.**

I. Introduction

A characteristic of electrodermal activity is that it changes with time, and the change is divided into tonic and phasic phenomena. The phasic phenomenon is known as a psychophysiological index called "galvanic skin reflex" (GSR). The phasic activity is a reaction to many kinds of external stimuli and may be completed in a few seconds. In the field of electrodermal instrumentation, attention has been given to the electrical properties of the skin during GSR [1].

Taking electrical resistive and capacitive properties of the skin into account, measuring impedance as an index of electrodermal activity and determining its frequency characteristic (*i.e.*, impedance locus) are useful in analyzing the electrical characteristic of the skin. In a phasic changing process such as during a GSR, only a measurement system which is fast enough to follow the phasic change can determine the frequency characteristics of impedance.

The determination of impedance is performed by means of a frequency-domain analysis or a time-domain analysis [2]. In frequency-domain analysis, since measurements are carried out at each and every frequency, it is difficult to obtain the overall frequency characteristics of impedance instantly. In particular, skin impedance, which is always changing, restricts the measurements, and frequency characteristics of the skin impedance during transient electrodermal activity are hard to determine [1]. By contrast, time-domain analysis has the advantage of being able to instantaneously determine all the frequency characteristics of the impedance [2]. Time-domain analysis therefore can follow a phasic activity such as a GSR and obtain frequency characteristics of the skin impedance during the activity. However, no measurement systems for this technique have been developed.

In this paper, we confirm that the principle of time-domain analysis can also be applied to skin impedance which varies with time. We have determined that the conditions present in the skin allow the use of this measurement method, and by so doing, a measurement system which can determine skin impedance instantly has been developed. The efficiency of this system is shown by its capacity to obtain the time course of the impedance locus.

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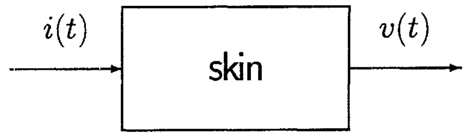


Fig. 1. Relationship between current $i(t)$ and voltage $v(t)$ of the skin.

II. Materials and Methods

A. Principle of Determining Impedance

Supposing that the characteristic of skin forms a linear system, the Fourier transforms of the current applied to the skin $i(t)$ and its voltage response $v(t)$ shown in Fig. 1 are $I(j\omega)$ and $V(j\omega)$, respectively; then the skin impedance $Z(j\omega)$ is expressed by the equation

$$Z(j\omega) = \frac{V(j\omega)}{I(j\omega)}. \quad (1)$$

When the current is the unit impulse $\delta(t)$

$$I(j\omega) = 1 \quad (2)$$

and $v(t)$ is equal to an impulse response $h(t)$. The skin impedance $Z(j\omega)$ can be determined by performing a Fourier transform of the impulse response using the equation

$$Z(j\omega) = \int_0^\infty h(t)e^{-j\omega t}\,dt. \quad (3)$$

Using the discrete style, we can obtain the impedance as

$$Z(j2\pi n\Delta f) = \Delta t \sum_{m=0}^{N-1} h(m\Delta t)e^{-j2\pi(nm/N)} \quad (4)$$

where Δt = sampling interval, N = data points and $\Delta f = 1/(N\Delta t)$.

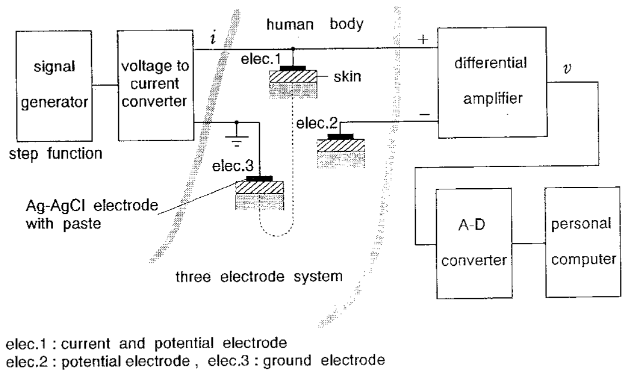


Fig. 2. Block diagram of measurement of electrical parameters in palm skin.

However, it is difficult to generate an impulse signal and then obtain the impulse response. Consequently, we measured the step response since the impulse response $h(t)$ can be expressed using the step response $A(t)$, which is easily measured, as

$$h(t) = \frac{dA(t)}{dt}. \tag{5}$$

B. Skin impedance and the Circular Arc Law

It is known that skin impedance satisfies the circular arc law [3], as impedances of various biological tissues also do. The skin impedance Z can be expressed by

$$Z = \frac{Z_0}{1 + (jf/f_m)^\beta} \tag{6}$$

where $\lim_{f\to\infty} Z = 0$, the impedance at zero frequency is Z_0, the frequency at which the reactance is a maximum is f_m, and a fractional power related to the arc's angle is β. Z_0, f_m and β are termed the 'parameters of the circular arc law.' The characteristics of the impedance Z form the impedance vector locus. The center of this lies below the real axis and has a continuously distributed relaxation time. In order to determine the characteristics of impedance Z, one must measure a set of impedance values at many frequencies. However, since the impedance Z can be expressed by (6), one will obtain the values of the impedance Z at all frequencies when determining the three parameters Z_0, f_m and β. The three parameters Z_0, f_m and β are therefore useful to express the skin impedance and for the applied analyses.

C. Measurement System

Fig. 2 is a block diagram of the complete system of measuring the transient response. The output step voltage from the generator is converted to a current of the same phase angle and waveform by a voltage-to-current converter, and this current flows through the skin via electrodes 1 and 3. The voltage drop, which is the step response, of the impedance of the skin under electrode 1 is amplified by a differential amplifier. The response waveform which is quantized by an A/D converter is input to a personal computer. The sampling interval is 50 μs or 200 μs. The data are then saved on a floppy disk and analyzed by a personal computer after measurement.

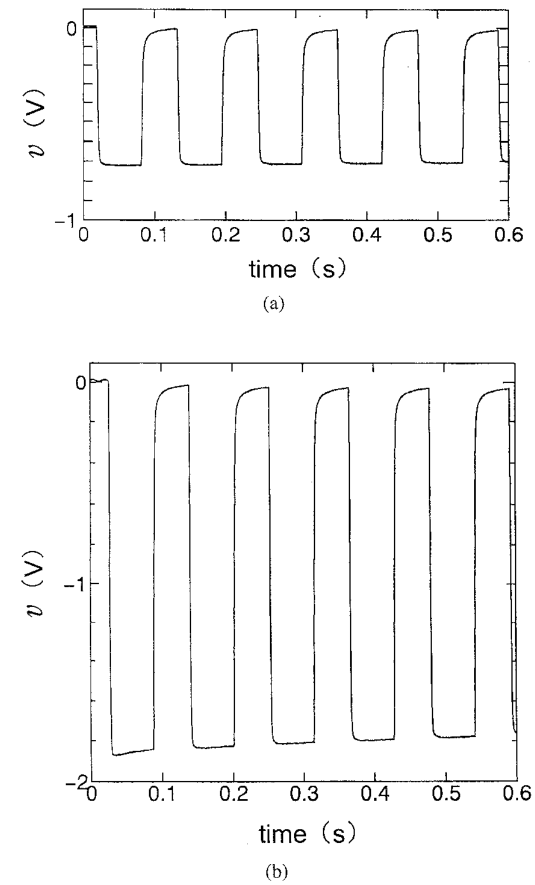


Fig. 3. Waveforms of repetitive step responses. (a) $i = -10\,\mu$A; (b) $i = -50\,\mu$A.

The sequence of the analysis by the computer is as follows. (1) 512 data points for a step response waveform are picked up from the floppy disk. These data are differentiated numerically. The numerical differentiation is performed with the central difference representation. These data are treated as an impulse response. (2) The FFT is performed for the impulse response. Thereby, the skin impedance is determined. (3) The parameters of the circular arc law are calculated using this determined impedance.

We adopted a three-electrode technique [4] as an electrode system using Ag-AgCl electrodes (skin surface electrode, Nihon Kohden Co.Ltd, Japan), which were unpolarizable and 10 mm in diameter. The electrode paste used was a cream (Redux cream, Hewlett Packard, U.S.A.).

III. Results and Discussions

A. Nonlinear Electrical Property of the Skin

In transient response, the object must be a linear system. We therefore need to investigate the linearity of the skin impedance, which essentially has nonlinear characteristics. The linearity of the skin impedance in the step response is dependent on current flow. Fig. 3 shows the waveform of the step response, when the rectangular current flows continuously to the skin. The period of repetition is 0.1 s. The flow period is

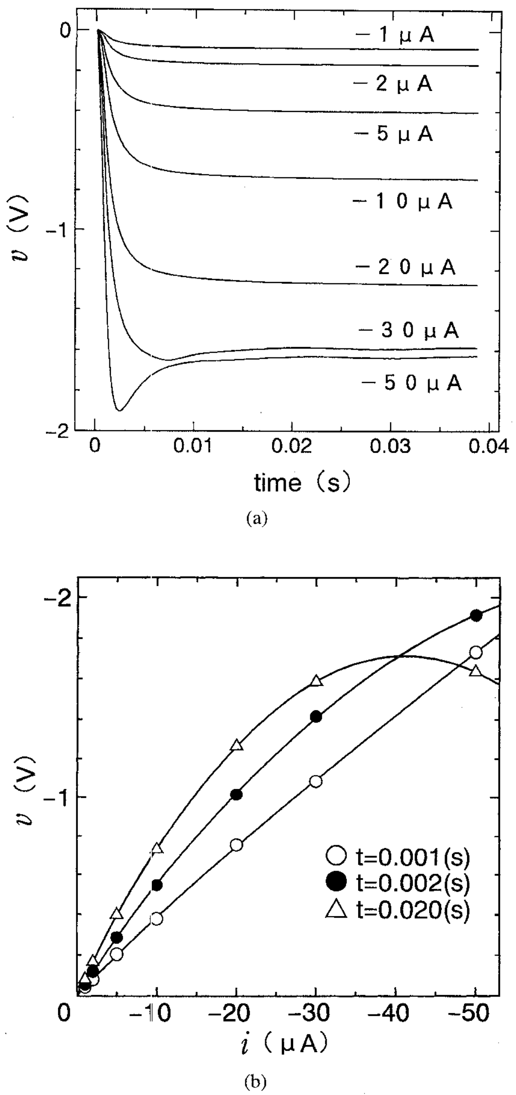


Fig. 4. Nonlinearity of step response of the skin. (a) Responses for various current values; (b) linearity of response.

0.05 s. When current density is $-10\,\mu$A as shown in Fig. 3(a), peak-to-peak values are constant. The minus polarity is defined by the current direction flowing from inner tissues to the skin surface. The skin potential level (SPL) in the repetitive response does not change before or after the flow. On the other hand, when the flow current density is $-50\,\mu$A as shown in Fig. 3(b), the skin potential level of the repetitive response gradually becomes smaller. The skin impedance is not influenced by the continuous current flow of 10 μA. Steady waveforms of the step responses can be sufficiently obtained during several seconds of GSR appearance.

Fig. 4(a) shows the step response of skin impedance in the forearm using several values of current. There is a linear relationship between flow current and voltage response when the current is smaller than 10 μA (*i.e.*, 12.7 μA/cm^2). The linear relationship disappears at higher currents. Fig. 4(b) shows the relationship between flow currents and voltages which are the values at times $t = 0.001$ s, 0.002 s, 0.020 s in

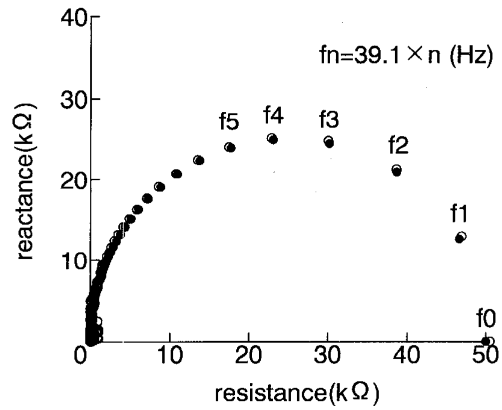


Fig. 5. Measurement result of equivalent circuit. o: measured value; •: theoretical value. The impedances at frequencies fn which are n times as high as $\Delta f(= 1/(N\Delta t))$ can be obtained. $N = 512, \Delta t = 50\,\mu$s and $\Delta f = 39.1$ Hz.

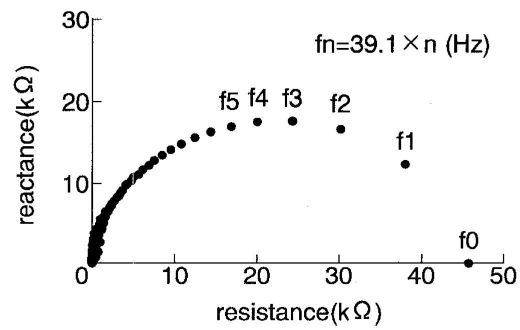


Fig. 6. Skin impedance on the palm site.

each response waveform in Fig. 4(a). If skin impedance is a linear system, there is a linear relationship between current and voltage with time t. Accordingly we find there is a linearity below 10 μA, and the nonlinearity appears above 20 μA. Skin impedance is greatly influenced by measurement conditions. A low current should not be used in order to avoid the influences caused by noise from the standpoint of measurement. The appropriate current value changes in each case [5].

B. Accuracy of the Measurement Method

In order to investigate the accuracy of impedance measurement by a transient response method, the RC parallel circuit is measured. It is well known that an electrical equivalent model of the simple RC parallel circuit approximately represents its electrical characteristics. Considering the properties of actual skin, the values of the circuit elements were given as 50 kΩ and 0.022 μF. The step response of this model circuit to a current flow of 10 μA was recorded. The sampling interval Δt is 50 μs, and the number of samples is 512. The impedance was determined by the method as previously stated. Fig. 5 shows vector loci of theoretical values and measured values obtained by the transient response method. The vector locus of the measured values is quite similar to that of the theoretical values. It shows an arc locus of a perfect semicircle. The measured value has some dispersion

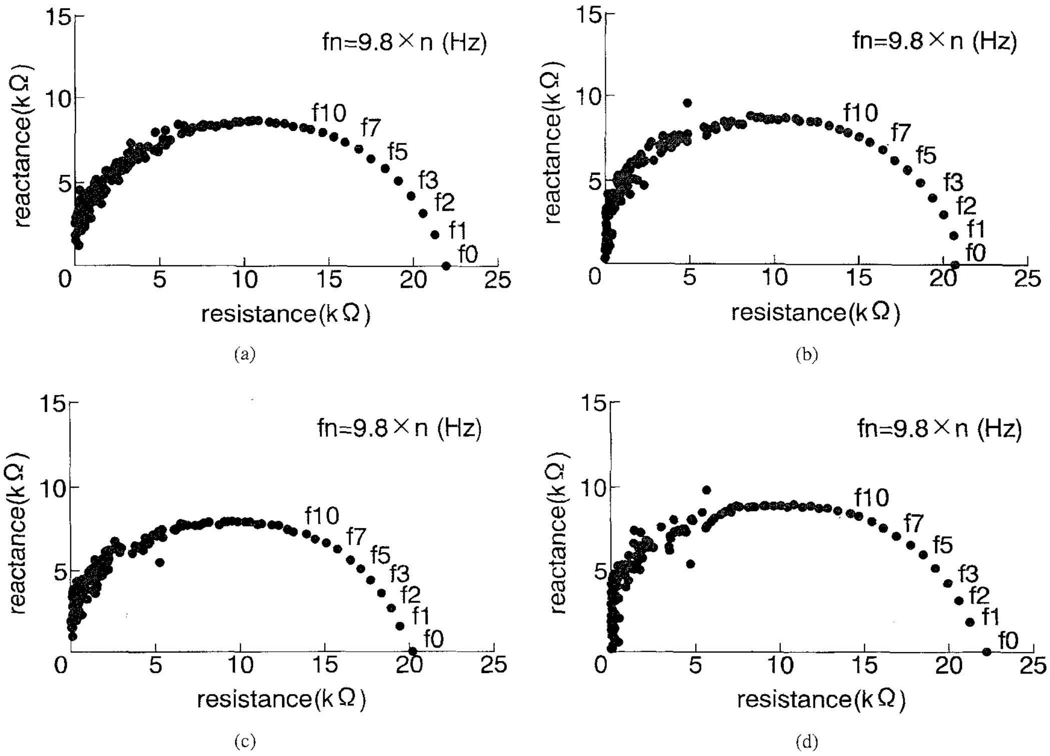


Fig. 7. Impedance during a GSR. (a) t_1; (b) t_2; (c) t_3; (d) t_4. $N = 512$. $\Delta t = 200\,\mu s$ and $\Delta f = 9.8$ Hz.

differences in its frequency range above 1 kHz. This is not a serious problem because differences in the high-frequency range do not influence the determination of the arc locus. It is difficult to obtain an accurate value at high frequencies by calculating the FFT. But considering that the measured points from 0 Hz to 400 Hz plot about 3/4 of the arc, and the vector locus of the skin impedance passes through the origin, the arc locus can be determined accurately for these measurement conditions in this frequency range. The results of the measurement show that the relative error of measured values to the theoretical values is less than 2%. The accuracy is sufficient to measure impedance.

Fig. 6 shows the results of the measurement of skin impedance. The flow current is 10 μA, and the step response is measured with a 50 μs sampling interval and 512 sampling points. Although there are some differences with the high-frequency range compared with the low-frequency range, the arc locus can be determined with certainty.

C. Determination of the impedance during a GSR

GSR is a phenomenon during which the electrical property of the skin varies instantaneously. The duration time of variations is 3–5 s. Hence it is difficult to obtain the change of the frequency characteristics of impedance by a frequency-domain analysis. But, impedance can be measured by the transient response method, and this is used to determine impedance during GSR.

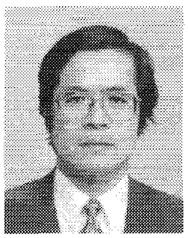
Fig. 7 shows changes of impedance during GSR. The step responses are measured in a 200 μs sampling interval at 512 sampling points. The arc locus changes with time. The property of the skin impedance is presented using parameters of the circular arc law Z_0, f_m and β. These parameters are calculated using each arc. We find that β hardly changes. The skin impedance during GSR appearance, which had been estimated with insufficient measurement data, is confirmed using these transient response methods.

IV. CONCLUSION

A new method of instantaneously determining a skin impedance which changes transiently with time has been developed. The total frequency characteristics of skin impedance are determined using time-domain analysis. This method has the advantage of instantaneous determination of impedance compared with conventional methods using frequency-domain analysis. The skin impedance during GSR appearance can be determined using time-domain analysis. The new measurement method for skin is useful for detailed analysis of various characteristics during GSR.

REFERENCES

[1] W. Boucsein, *Electrodermal Activity*. New York: Plenum, 1992.
[2] H. P. Schwan, "Determination of biological impedance," in *Physical Techniques in Biological Research,* vol. 6, W. L. Nastuk, Eds. New York: Academic, 1963, pp. 323–407.
[3] K. S. Cole and R. H. Cole, "Dispersion and absorption in dielectrics, I—Alternating current characteristics," *J. Chem. Phys.,* vol. 9, pp. 341–351, 1941.
[4] Y. Yamamoto, "Measurement and analysis of skin electrical impedance," *Acta Derm Venereol,* Suppl. 185, pp. 34–38, 1994.
[5] T. Yamamoto and Y. Yamamoto, "Non-linear electrical properties of skin in the low frequency range," *Med. Biol. Eng. Comput.,* vol. 19, pp. 302–310, 1981.



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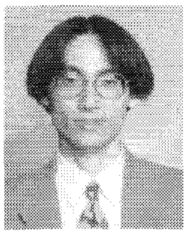

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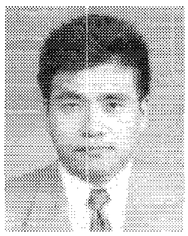

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