Influences of the Skin Impedance as the Interface in Bioelectric Potential Measurement

Yoshitake YAMAMOTO* and Tatsuma YAMAMOTO*

Synopsis

In the case of non-invasive measurement of bio-electric potential from body surface, the influence of the skin impedance has been investigated by using strict equivalent circuits of skin impedances. The relationship between the characteristic of skin imped-ance and the wave distortion was made clear.

Furthermore, in the case of electrocardiograph, the shift potential of indifferent electrode to stand-ard potential was obtained by means of simulation, and the distortions caused by connective resistances of a central terminal and skin impedance were quantitatively explained.

1. Introduction

In the early state of the development of electrocardiography (ECG) and electroencephalography (EEG), the influences of the skin impedance to these wave forms were very large. Then, the various contrivances for reducing the influence of the skin impedance have been conducted. Nowadays, the influence of the skin impedance became small with the development of electronic amplifier. However, the accuracy required for the waveforms is progressively increasing. It is necessary to grasp precisely the situation of the waveform distortion by the skin impedance. Then, the problems of the skin impedance are examined by

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* Department of Electrical Engineering

using the equivalent circuit of skin impedance from a point of view
as the interface for bio-measurement amplifier. The wave form dis-
tortions caused by the skin impedance are obtained and examined in
the relationship with the characteristic of skin impedance.

2. Equivalent Circuits of Skin Impedance and Interface Design

    Considering the conjunction of biological tissue and instrument
in the bioelectric potential measurement, it is necessary that the
input impedance of an instrument is much larger than the electrode
polarization impedance and than the skin impedance in order to trans-
mit correctly the signal. The input impedance of the instrument has
been decided by JIS(Japanese Industrial Standard)[1] more than 1 MΩ
for ECG, 5 MΩ for EEG and 2 MΩ for EMG. Althogh the input impedance
of preamplifier is able to prepare extremely large, it should be
limited up to 10 MΩ because of the capacity of the input cable and
so on. In comparison with this value, the skin impedance is scatter-
ing and can become several $MΩ.cm^2$ as the extrapolated value (Z_0 or R_2)
of zero frequency ($f = 0$)[2]. The problems of skin impedance become
especialy serious in the case of small electrode area.
    Now, the problems of the skin impedance as the interface of an
instrument is examined by using the equivalent circuit with fixed
elements for skin impedance[3]. The parameters of skin impedances
and values of circuit elements prepared are given as shown in Table 1.
The frequency characteristics of equivalent circuit is shown in Fig.1.
The area of skin i.e. of electrode is assumed as 1 cm^2 and 10 cm^2,
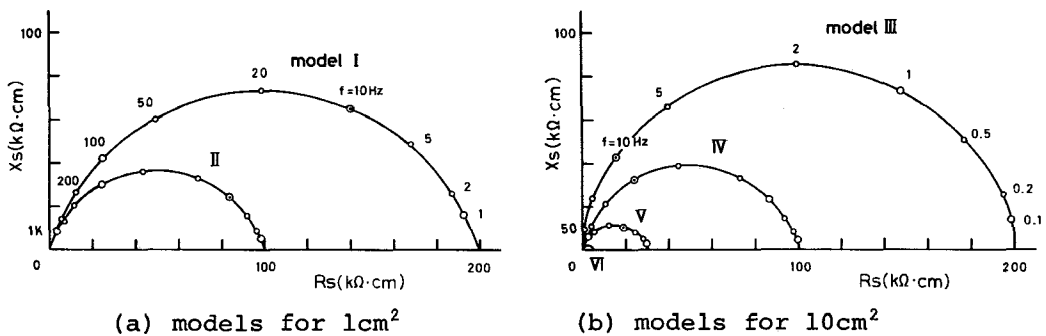and the impedance (Z_∞) obtained as the extrapolated value of infinite

(a) models for 1cm^2 (b) models for 10cm^2

Fig.1 Vector loci of model equivalent circuit.

Table 1 PARAMETERS OF EQUIVALENT CIRCUIT

	Z_0 (kΩ)	β	f_m (Hz)	S (cm²)	Values of Equivalent Circuit Elements				
					1	2	3	4	5
I	200	0.8	20	1	R(kΩ) 9.40	44.60	92.00	44.60	9.40
					C(μF) 21.39	0.557	0.0865	0.0572	0.0335
II	100	0.8	40	1	R(kΩ) 4.70	22.30	46.00	22.30	4.70
					C(μF) 21.39	0.557	0.0865	0.0572	0.0335
III	200	0.9	2	10	R(kΩ) 30.38	139.24	30.38		
					C(μF) 9.35	0.571	0.734		
IV	100	0.85	4.3	10	R(kΩ) 3.3	19.7	54.0	19.7	3.3
					C(μF) 250.	5.35	0.689	0.659	0.502
V	30	0.83	15	10	R(kΩ) 1.13	6.42	14.9	6.42	1.13
					C(μF) 204.	4.83	0.707	0.551	0.389
VI	5	0.8	105	10	R(kΩ) 0.235	1.115	2.30	1.115	0.235
					C(μF) 163.	4.24	0.659	0.436	0.255

frequency ($f = \infty$) are assumed as zero. In the case of large valus of
β as model III, even three couples of RC element can simulate well a
skin impedance. Besides these models, two models are prepared as (1)
pure resistance model of 200 kΩ and (2) Debye type model constructed
with two parallel elements of resistor 200 kΩ and capacitor 0.04 μF.

When the input impedance of an instrument amplifier is assumed
as 1 MΩ, the characteristics of signal distortion are shown in Fig.2
for skin impedance models as follows:

    (1) pure resistance : 200 kΩ
    (2) Debye type : 200 kΩ, 0.04 μF, β = 1
    (3) Cole-Cole type : I (1 cm²)
    (4) Cole-Cole type : III (10 cm²)

The influences of electrode polarization impedance have been reported
in detail[4][5] and are ignored in present examinations. The signal
distortion is varied naturally when the value of Z_0 is changed.
However the differences of the distortion due to the types of model
can be estimated quantitatively. The skin impedance is the Cole-
Cole type and causes the signal distortion as shown in Fig.2(3).
The case of the Debye type is shown in Fig.2(2). Both cases have
the characteristic of differentiation which decreases greatly the com-
ponent of lower frequency. However, the attenuation characteristics
are different in both cases. In the case of the pure resistance, the
distortion for frequency is absent and flat as shown in Fig.2(1).
In the case of the electrode area of ten times, the characteristics
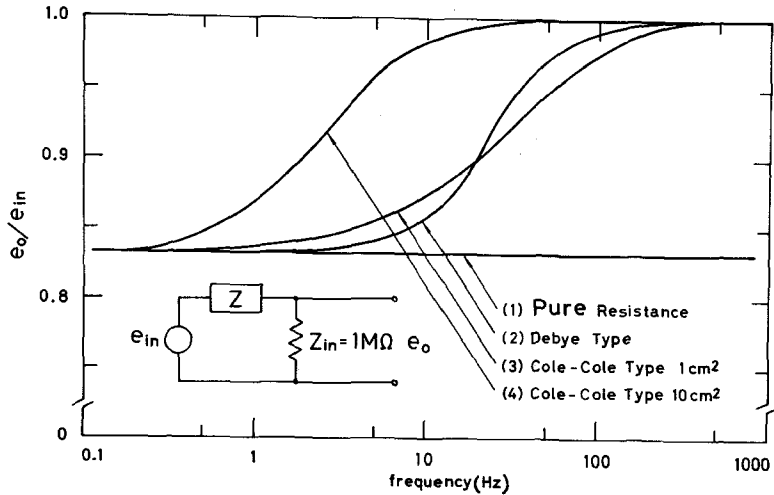
(a) gain characteristic
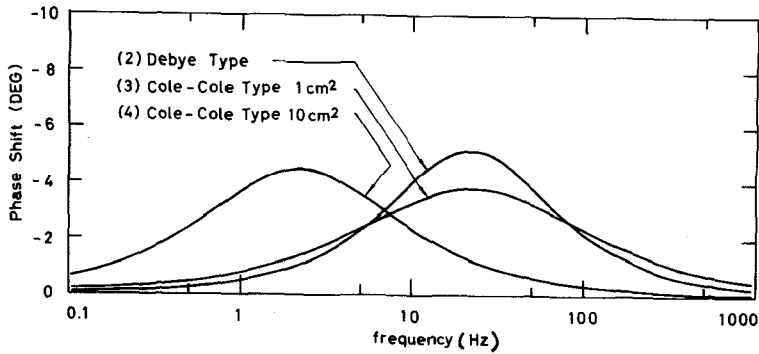
(b) phase characteristic

Fig.2 Characteristics of signal distortion due to
the several types of model.

of gain and phase are shifted to the side of lower frequency and the
distortion becomes lower in spite of same 200 kΩ as shown in Fig.2(4).
It is attributable to lowering the skin impedance because the capaci-
tance was assumed to the ten times proportional to the electrode area
considering the characteristic of skin impedance. When the electrode
area becomes ten times in the actual skin, the extrapolated resist-
ance Z_0 of zero frequency becomes 1/10. Therefore, the electrode of
large area has notable merit for the purpose of avoiding the wave
distortion. When the resistance Z_0 becomes large, the frequency
point of maximum phase angle is shifted. But, the phase angle becomes

larger and the gain characteristic goes wrong.

3. Influences of Skin Impedance to the Distortion of Electrocardiography

Many researches have been reported to the influences of skin impedance to electrocardiography[6][7]. However, the pure resistance model as the equivalent circuit of skin impedance was mostly used and was not precise in the case of examinations for wave distortion due to the simulation. In this paper, the equivalent circuits of the Cole-Cole type are used as the equivalent circuits for skin impedance. The detailed examinations can be executed by the comparison of wave forms which are yielded in the cases of present and absent of circuits. The block diagram of the measurement circuit is shown in Fig.3. The potentials (R, L, F, V) induced in each part of body are amplified to 1000 times through buffer amplifiers and stored into four channel data recorder. The distortions of wave forms are examined with the regenerative wave forms from the data recorder. The input impedance of the electrocardiograph is 1 MΩ - 1 MΩ and the connective resistance of a central terminal is 30 kΩ[1].

Usualy, the skin impedance of an ankle is larger than the skin impedance of a wrist. Then, it is supposed that only the left foot in Fig.3 has the skin impedance (Z_F) of model II in Table 1. The induced wave forms in the cases of present and absent of Z_F are correspondingly shown in Fig.4. The standared limb leads (I, II, III) have little difference, the augmented unipolar limb leads (aVR, aVL,
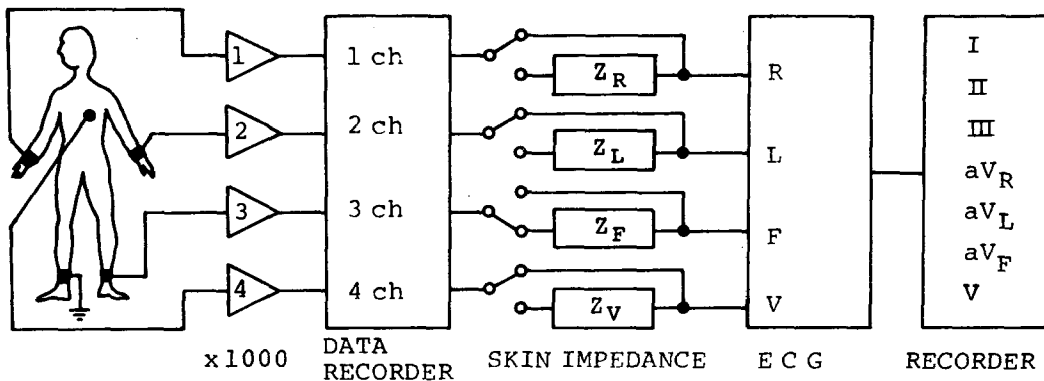

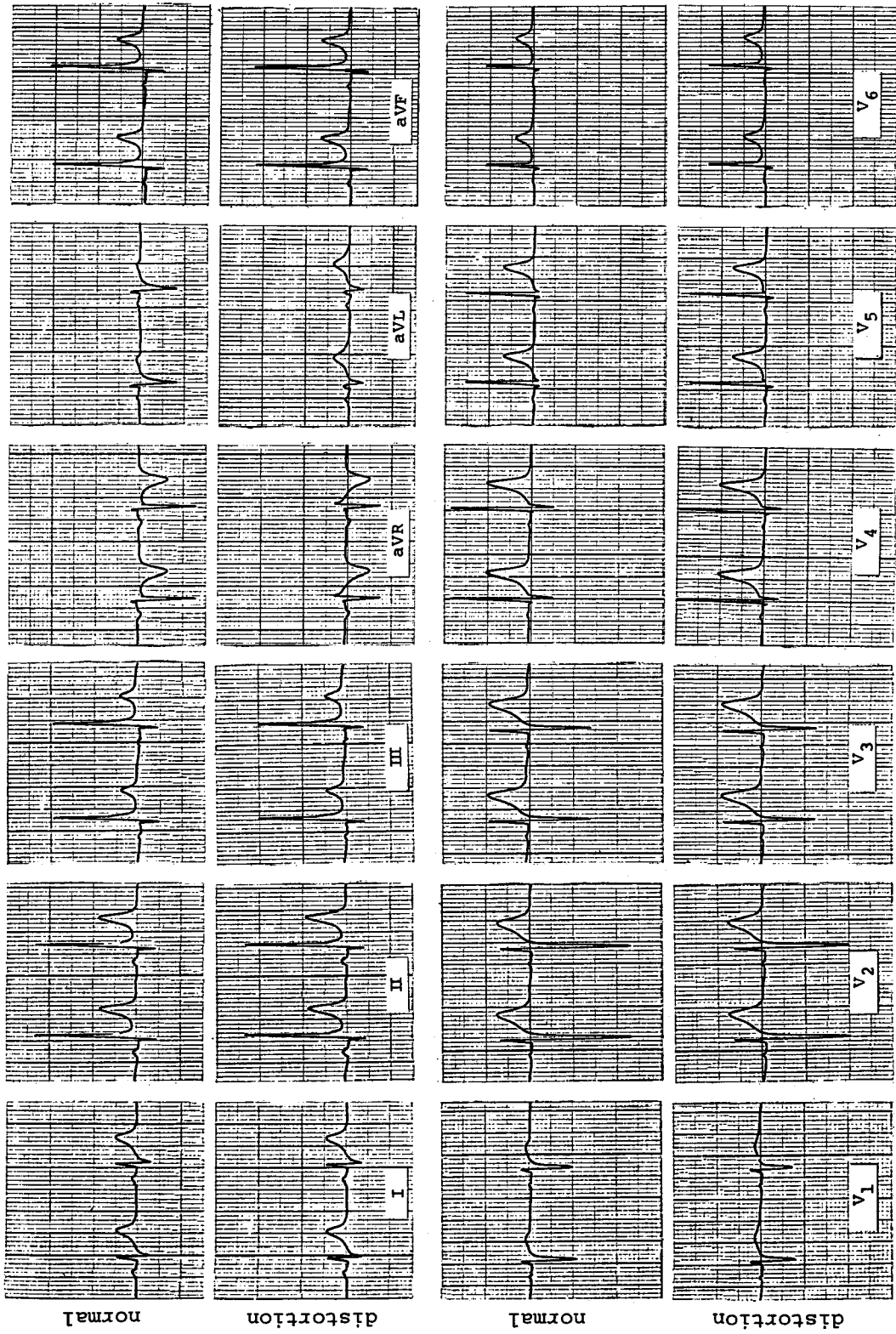Fig.3 Block diagram of measurement circuit of electrocardiography.

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Fig. 4 Normal wave forms and distorted wave forms of electrocardiography.

normal
wave form

P – P'

(a) $Z_R = 0$
$Z_L = 0$
$Z_F = 200k\Omega$ (1)

(b) $Z_R = 0$
$Z_L = 0$
$Z_F = 100k\Omega$ (1)

(c) $Z_R = 0$
$Z_L = 0$
$Z_F = 200k\Omega$ (10)

(d) $Z_R = 0$
$Z_L = 0$
$Z_F = 100k\Omega$ (10)

(e) $Z_R = 0$
$Z_L = 30k\Omega$ (10)
$Z_F = 200k\Omega$ (10)

P – P'

(f) $Z_R = 0$
$Z_L = 200k\Omega$ (1)
$Z_F = 0$

(g) $Z_R = 0$
$Z_L = 100k\Omega$ (1)
$Z_F = 0$

(h) $Z_R = 0$
$Z_L = 200k\Omega$ (10)
$Z_F = 0$

(i) $Z_R = 0$
$Z_L = 100k\Omega$ (10)
$Z_F = 0$

(j) $Z_R = 0$
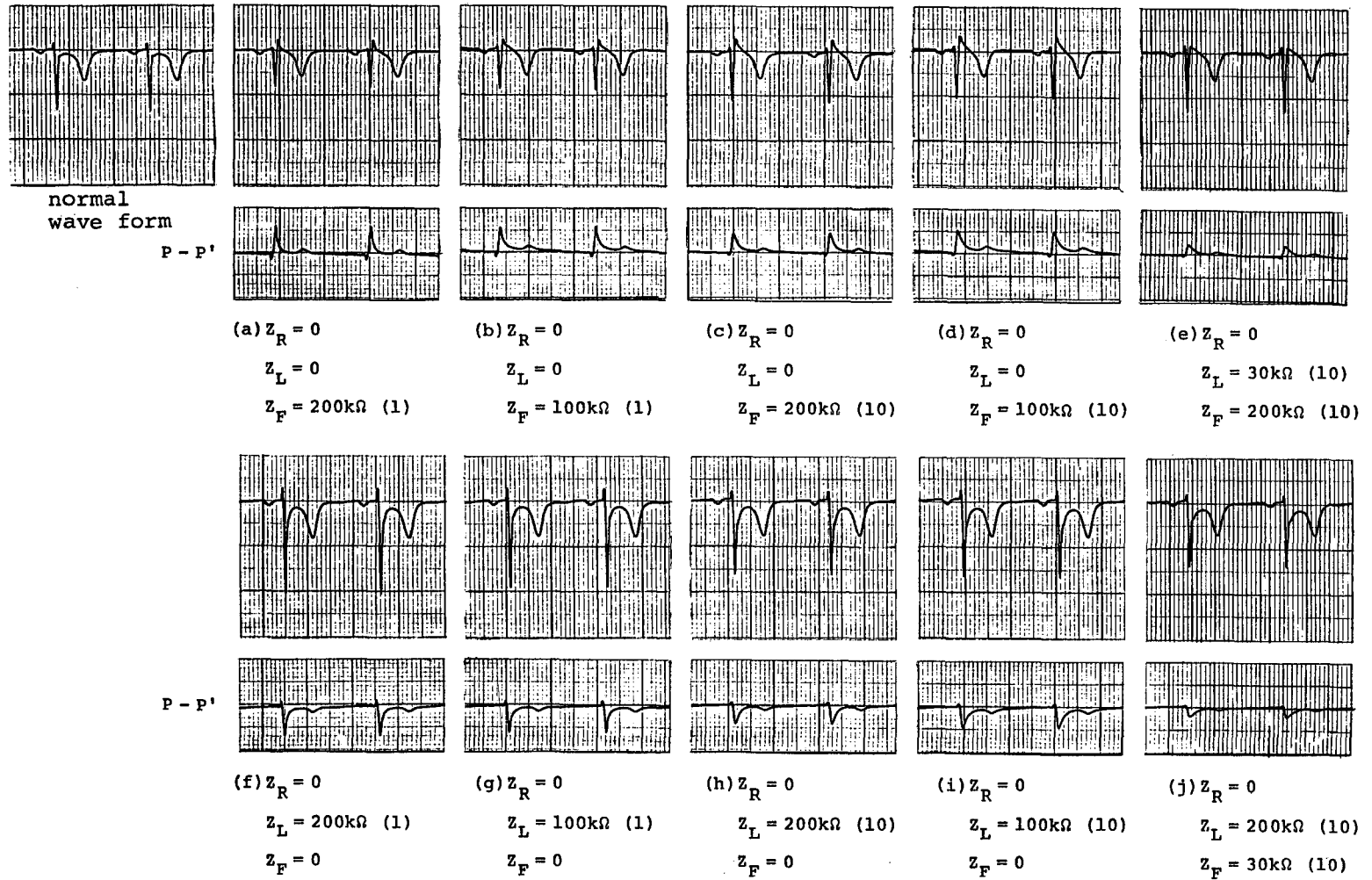$Z_L = 200k\Omega$ (10)
$Z_F = 30k\Omega$ (10)

Fig.5 Influences of skin impedance to the augmented unipolar limb leads aVR
and the shift of the standard potential.

aVF) have large difference and the precordial unipolar leads (V_1, V_2, V_3, ...V_6) have some difference. These are mainly caused that the standard potentials of Goldberger and Wilson connective electrodes shift by the skin impedance Z_F. In the aVR leads of augmented unipolar limb leads, wave form distortions and the shift of standard potential induced by the skin impedance of each part are shown in Fig.5. Equivalent circuits used to limb electrodes are given in Table 1. The shifts of standard potential $p-p'$ have been recorded with sensitivity (0.5 mV/10 mm) as same as electrocardiography. The skin impedance is larger and the area of skin (i.e. electrode) is smaller, the wave form distortion becomes larger. And as well known, the unbalance of skin impedance is larger, the distortion becomes larger.

Schwarzschild et al.[6] have reported about the shift of potential of the connective electrode using the skin impedance model of pure resistance. Now, further strict examination is proceeded in consideration of the frequency characteristic of skin impedance. In order to estimate the frequency characteristic, wave forms of each limb leads potentials and standard limb leads are expanded to the Fourier series as follows;

$$\left.\begin{array}{lll} R = \sum_{\omega} \mathscr{R}(\omega), & L = \sum_{\omega} \mathscr{L}(\omega), & F = \sum_{\omega} \mathscr{F}(\omega) \\ I = \sum_{\omega} \mathcal{I}(\omega), & II = \sum_{\omega} \mathcal{II}(\omega), & III = \sum_{\omega} \mathcal{III}(\omega) \end{array}\right\} \tag{1}$$

In the Goldberger connective electrode as shown in Fig.6, when the skin impedance is absent, the standard potential X_{AVRO} of a point p

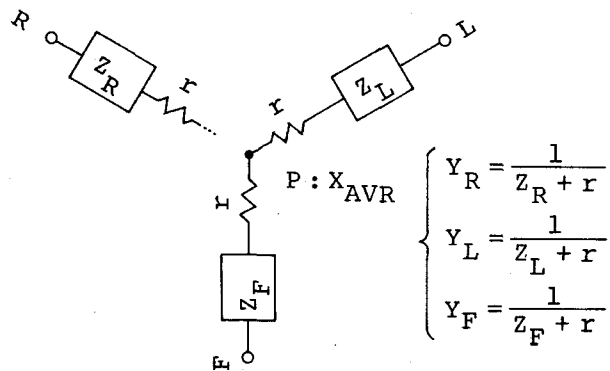$$Y_R = \frac{1}{Z_R + r}$$
$$Y_L = \frac{1}{Z_L + r}$$
$$Y_F = \frac{1}{Z_F + r}$$

Fig.6 Goldberger's connective electrode (aVR).

can be expressed as follows;

$$X_{AVRO} = \sum_{\omega} \mathcal{X}_{AVRO}(\omega)$$

$$= \sum_{\omega} \frac{\mathcal{L}(\omega) + \mathcal{F}(\omega)}{2} \tag{2}$$

when the skin impedances are presented, the standard potential of a point p (i.e. p') becomes

$$X_{AVR} = \sum_{\omega} \mathcal{X}_{AVR}(\omega)$$

$$= \sum_{\omega} \frac{Y_L \mathcal{L}(\omega) + Y_F \mathcal{F}(\omega)}{Y_L + Y_F} \tag{3}$$

Therefore, the shift $(p - p')$ of the standard potential is

$$X_{AVRO} - X_{AVR} = \sum_{\omega} (\mathcal{F}(\omega) - \mathcal{L}(\omega)) \frac{Y_L - Y_F}{2(Y_L + Y_F)}$$

$$= \sum_{\omega} \mathcal{III}(\omega) \frac{Y_L - Y_F}{2(Y_L + Y_F)} \tag{4}$$

It has been multiplied by the coefficient to the III lead of standard limb leads. Its coefficient is depending to a frequency.

The shifts $(p - p')$ of potential for the augmented unipolar limb leads aVL and aVF and for the precordial unipolar leads V are given respectively as follows;

$$X_{AVLO} - X_{AVL} = \sum_{\omega} \mathcal{II}(\omega) \frac{Y_R - Y_F}{2(Y_R + Y_F)} \tag{5}$$

$$X_{AVFO} - X_{AVF} = \sum_{\omega} \mathcal{I}(\omega) \frac{Y_R - Y_F}{2(Y_R + Y_F)} \tag{6}$$

$$X_{VO} - X_V = \sum_{\omega} \frac{\mathcal{R}(\omega) + \mathcal{L}(\omega) + \mathcal{F}(\omega)}{3}$$

$$- \sum_{\omega} \frac{Y_R \mathcal{R}(\omega) + Y_L \mathcal{L}(\omega) + Y_F \mathcal{F}(\omega)}{Y_R + Y_L + Y_F} \tag{7}$$

In the case of aVR, when $Z_L = 0$ and $Z_F =$ model II or model III (Table 1) are assumed, the coefficients of eq(4) expressed by eq(8) have the frequency characteristic as shown in Fig.7.

$$K \angle \theta = \frac{Y_L - Y_F}{2(Y_L + Y_F)} \tag{8}$$

If the fundamental component of QRS wave is considered as 10 Hz, the coefficients are 0.367 for model I and 0.255 for model III. On the other hand, the ratio of QRS wave in the corresponding of III lead in Fig.4 and $p - p'$ in Fig.5 are 0.3 in the case of model I(a) and 0.2 in the case of model III(c). These coefficients became small value than former coefficients because of the high frequency components included in the waves.

· Skin impedances fluctuate considerably due to various factors. Then, it is not sufficient that the examination have been done by only the special models for skin impedance. However, the strict estimation of its influences can be performed by the model of Cole-Cole type instead of the customary model of pure resistance.

The wave form distortions for the one channel electrocardiograph were examined in accordance with JIS of electrocardiographs[1]. The connective resistances of multichannel electrocardiograph are provided more than 200 kΩ by JIS. However, the influences of skin impedance are larger than the case of one channel because the connective
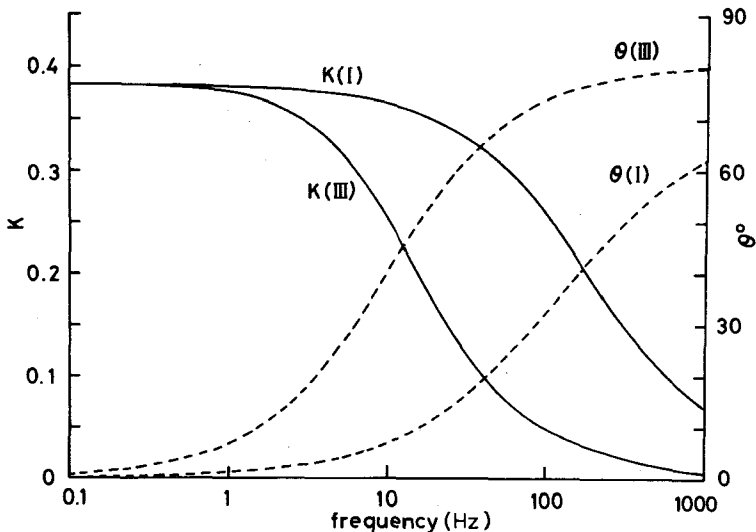

Fig.7 Coefficients of the shift of the standard potential.

resistances are connected simultaneously. Then, it is necessary that the connective resistances relation to the distortion are set to more large value in order to avoid the influences of skin impedance to electrocardiography. And the input impedance of the amplifier must become large sufficiently. Some of the latest one channel electrocardiographs have the connective resistance of 60 kΩ and input impedance of 5 MΩ exceeding the values of JIS. Multichannel electrocardiography mostly have the buffer amplifiers to electrodes of four limb leads and biopotential signals whose impedance is transformed are supplied to the connective resistances. The best method to avoid the influences of skin impedance is to provide the buffer amplifiers to all lead electrodes.

4. Conclusions

The investigation of the skin impedance as the interface in bioelectric potential measurement has been performed. Namely, how are the potential wave forms distorted have been definitely shown from the relationship between the input impedance of the instrument and the skin impedance using the each model of equivalent circuit for skin impedance. Cencerning the leads of the electrocardiographs whose indifferent electrode are constructed with the resistors connecting the electrodes, the potential differences between indifferent electrode and standard potential were separated. The wave form distortions were quantitatively explained. Further, the skin surface electrodes using to bioelectric potential measurement were examined from the standpoint as the interface.

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