

Modelling of interface construction relating to power-line interference phenomenon in biopotential signal measurement system

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Summary

A modelling of interface construction relating to power-line interference phenomenon was described. Source of interference was displacement currents which flowed from AC power-line configuration (APC) to a model. The interference depends on some factors: distance between the APC and a model; length of unshielded leads; position of the APC in vertical or horizontal direction; and skin-electrode impedances which were balance or unbalanced.

The position of APC and skin-electrode impedances were important in contributing of the interference. The interference was still large even though skin-electrode impedances were balance. This was caused by the disagreement in two displacement currents. It was overcome by adjustment of APC in vertical direction. As a result, total interference would be very small or zero.

The result shows that interference in ECG signal recording can be eliminated to about 10 μ V. Although interference of power-lines is a complicated phenomenon, the problem is easier to understand by using this modelling.

Key words : AC power-line configuration (APC), biopotential signal, displacement current, physical model of interference, power-line interference

Introduction

A major source of interference is power-line system when the biopotential signal is recorded or monitored. Besides providing power to the equipment of the biopotential signal recording, power-lines are connected to other pieces of equipment in the typical hospital room or physician's office. There are also power-lines in the walls, floor, and ceiling running past the room to other points in the building. These power-lines will affect the recording of the biopotential signal and introduce interference at the line frequency in the recorded trace¹⁾.

Some researchers analyzed the sources of

power-line interference caused by a displacement currents and electromagnetic induction. If the two leads that connect the subject and the bioamplifier form a loop, the electromagnetic field passes through the loop and induce electromotive force into the circuit. This voltage is proportional to the strength of the electromagnetic field, so that one solution to decrease the effect of electromagnetic field is to separate the source and the loop. It is also proportional to the area of the loop, and another solution is to minimize this area or by using inverse loop method^{2,3)}.

Displacement currents, which depend on the electric field surrounding of power-line and

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power cords connecting different pieces of apparatus to electrical outlets, can enter to the leads system and the body by capacitance coupling. These displacement currents flow through the skin-electrode impedance. Resulting voltage drop causes interference in output of the amplifier. The solution to decrease this problem are using the driven-right-leg amplifier and abrading the skin where the electrodes is placed⁴.

The analysis of interference is complicated because most modern biopotential amplifier contains an isolation barrier for protecting the patient from microshock and many sources of interference around the measurement system⁴. In order to understand the phenomenon of induced potential by displacement currents easily, a modelling of interface construction relating to power-line interference phenomenon is proposed. Then, a basic equation by other researchers² is used to evaluate of the interference and ECG signal is employed as one sample of real biopotential signal. The goal of this paper is how to understand easily some effects of power-line interference phenomenon especially by displacement currents induced into a model. A detailed knowledge of the phenomenon can be applied to improve the quality of biopotential measurement.

Basic Theory

We considered a general equation for determining of power-line interference in ECG measurement system using three electrodes with the subject grounded. The general equation is as follows²,

$$V_n = 2\pi fSB + (I_{d1}Z_{e1} - I_{d2}Z_{e2}) + I_bZ_b + V_{cm} \left(\frac{1}{CMRR} + \frac{Z_{e1} - Z_{e2}}{Z_{cm}} \right) \quad (1)$$

electromagnetic induction *induced potential by displacement current in leads* *induced potential by displacement current in body*

common mode potential *potential divider effect*

where,

- f frequency of power-line
- S area of loop
- B magnetic flux density

$CMRR$ common-mode rejection ratio

I_b displacement current coupled into body

I_{d1}, I_{d2} displacement current coupled into input leads

V_{cm} common-mode body potential with respect to ground

V_n total AC power-line interference

Z_{cm} common-mode input impedance of amplifier

Z_{e1}, Z_{e2} skin-electrode impedance

Z_b internal body impedances.

Huhta and Webster commented that not all sources of power-line interference would produce noticeable interference in all situations², that means are : (a) interference from electromagnetic induction can be minimized by twisting of the electrode leads ; (b) interference from displacement currents through the body tissue is neglected because the internal body impedances is very small ; (c) interference by common-mode body potential with respect to ground can be reduced by an adequate sharing between the common-mode and isolation rejection of the system. For most recording system, this interference can be negligible. However, in a practical system, the electrode leads can not be closed together completely and often leave a few centimeters of unshielded leads. As sequence, displacement currents of the two leads are not equal, $I_{d1} \neq I_{d2}$, and interference will be large. So that (1) for this case can be simplified as follows :

$$V_n = I_{d1}Z_{e1} - I_{d2}Z_{e2} \quad (2)$$

It will be used as a basic equation in this work.

Materials and Methods

1 Materials

The construction of the measurement system and an actual physical model are shown in Fig. 1 and Fig. 2, respectively. An actual physical model was a simple circuit which was connected with three resistors. Two of them, Z_1 and Z_2 (10 k Ω and 20 k Ω), were supposed as subject impedance and the other was Z_3 as ground impedance (10 k Ω). These resistors were con-

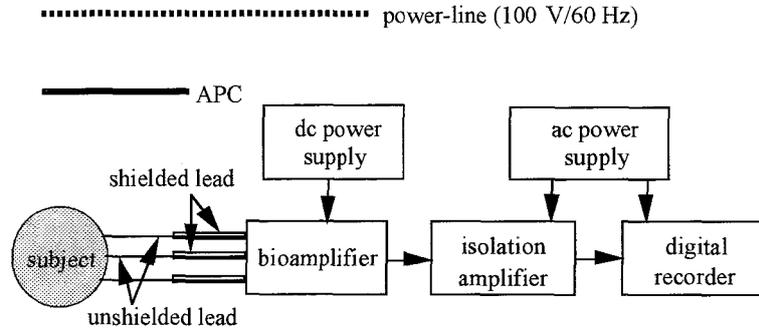


Fig. 1 General construction of the measurement system.

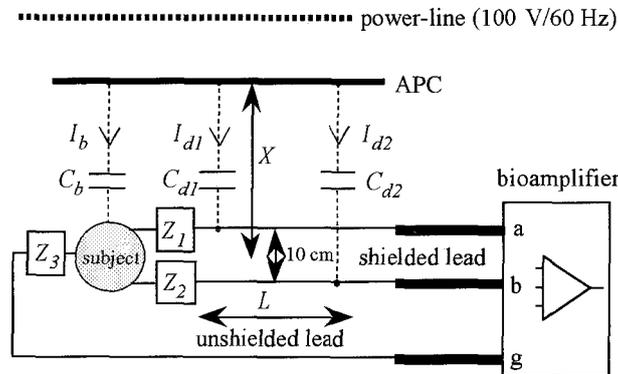


Fig. 2 Modelling of interface construction can be described as a conductor which connected to three resistors : Z_1 , Z_2 and Z_3 . Each resistors is supposed as subject impedance. L is length of unshielded leads and X is distance between APC and a model.

nected between electrode and leads (shielded- and unshielded leads) to the bioamplifier. Length of unshielded lead between electrode and the shielded lead were 5, 10, 20 cm. Because there were many points of power-line source around the model, we used a point as main-source of power-line. The frequency of power-line was 60 HZ. This source was called AC power-line configuration (APC).

We also performed the experiment to the human body, a health-male aged 37, as a subject and chose ECG signal as one of biopotential signal. In order to record this ECG signal with its interference, we adopted Lead I configuration and used three electrode system using Ag-AgCl electrodes (skin surface electrode Nihon Kohden Co. Ltd., Japan) which were unpolarizable 10 mm in diameter. The specification of bioamplifier is shown in Table 1. In addition, we also performed the experiment using skin-impedance balance controller.

Table 1 Specification of bioamplifier.

- CMRR (dB, 60 Hz)	99
- Total gain	500
- Input noise (μ Vpp)	6
- Cut-off frequency (Hz)	113
- Time constant (s)	1.5

2 Experimental procedure

1) A model

In order to acquire data of interference by displacement currents which flow from APC to a model, some procedures were carried out as follows: (a) two main resistors Z_1 and Z_2 ($Z_1=Z_2=20\text{ k}\Omega$ for balance and $Z_1=10\text{ k}\Omega$, $Z_2=20\text{ k}\Omega$ for unbalance) were connected to unshielded leads at various length: 5, 10, and 20 cm. The distance between these unshielded leads was 10 cm and the center of the distance was made as reference-point. From this point, APC was moved vertically or horizontally; (b) APC was set up its position in vertical or horizontal direction, respectively. Distances of APC to a model and

Table 2 Recording configurations.

Impedance (kΩ)	Direction	X^* (cm)	L^* (cm)
Balance ($R_1=R_2=20$)	horizontal and vertical	12.5 ; 25 ; 50 ; 100	5 ; 10 ; 20
Unbalance ($R_1=10, R_2=20$)	horizontal and vertical	12.5 ; 25 ; 50 ; 100	5 ; 10 ; 20

* L is length of unshielded leads and X is distance between APC and a model.

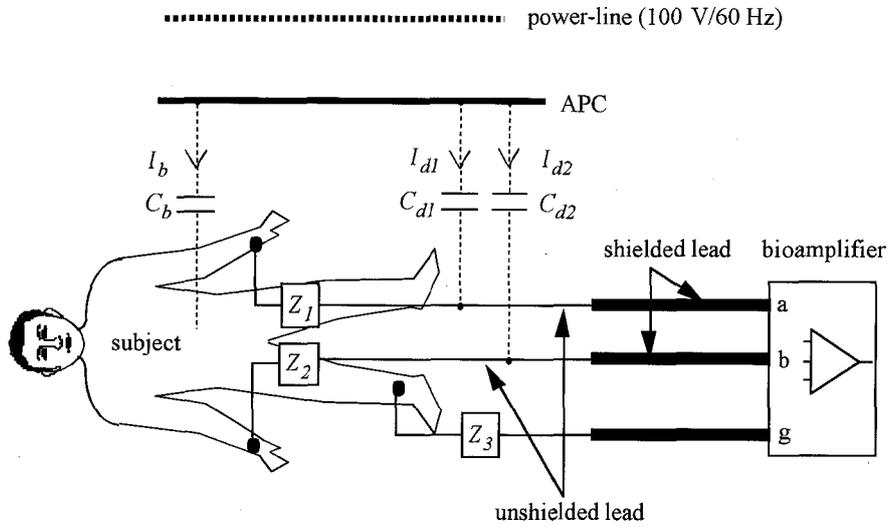


Fig. 3 Application of a model is in according with Fig. 2 for ECG signal recording.

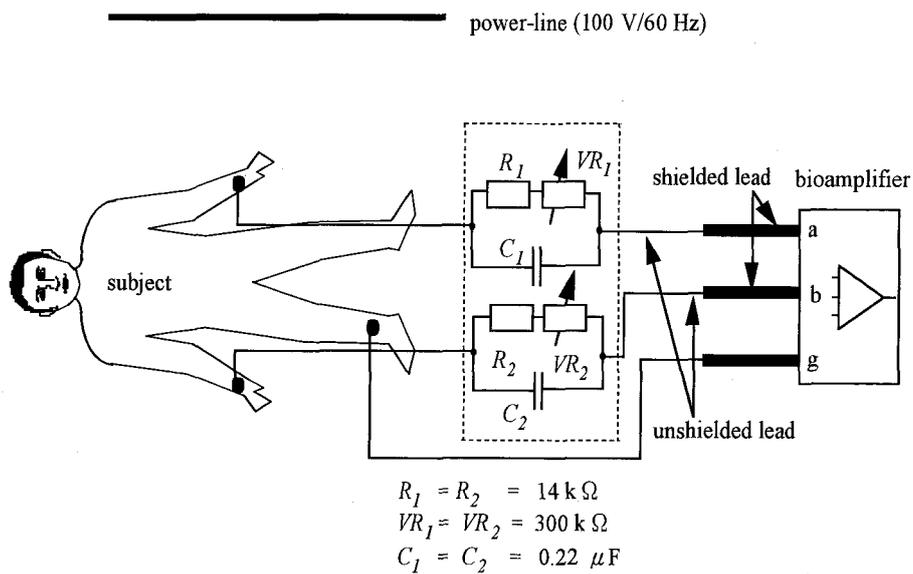


Fig. 4 Block diagram of a model and application of impedance balance controllers for ECG signal recording.

unshielded leads were 12.5, 25, 50, and 100 cm ; (c) Data were acquired for each unshielded lead with various distances in vertical and horizontal direction, respectively. A summary of recording configuration is given in Table 2.

2) Human body

The subject was lain on the bed in relax position as shown in Fig. 3. Procedure was the same as section 2.1). However, skin-electrodes were connected to resistors such as $Z_1=Z_2=10\text{ k}\Omega$ for balance and $Z_1=10\text{ k}\Omega$, $Z_2=0\text{ k}\Omega$ for unbalance ; length of unshielded lead was 20 cm ; and distance from APC to the subject was 50 cm. The skin-electrode impedances are typical value of usual⁵⁾.

3) Impedance balance controller

Impedance balance controller was a simple circuit of R-C parallel circuit⁶⁾ with variable resistor VR . VR was used as controller of skin-electrode impedance: balance or unbalance. Equation (2) was used as its basic equation and ECG signal recording was performed to test its performance. Recording of ECG signal was conducted in two steps. First, one of the VR was set to large value for skin-electrode impedance unbalance. Second, for skin-electrode impedance balance, both VR were set in order that interference was as small as possible. The APC did not used as source of displacement currents in this experiment. The block diagram of a model with a complete system of measurement ECG signal recording is shown in Fig. 4.

Results and Discussions

Displacement currents are capacitively coupled into the electrode leads from power-line and flowed through the skin-electrode impedances generating interference^{7,8)}. In practical system, because the leads are equal length and run close together, the two displacement currents are almost equal, $I_{a1}=I_{a2}=I_a$. Based on (2), the interference can be expressed as $I_{a2}(Z_{e1}-Z_{e2})$. This unbalance, $(Z_{e1}-Z_{e2})$, can be reduced to a few kilo-ohms at the power-line frequency by prepar-

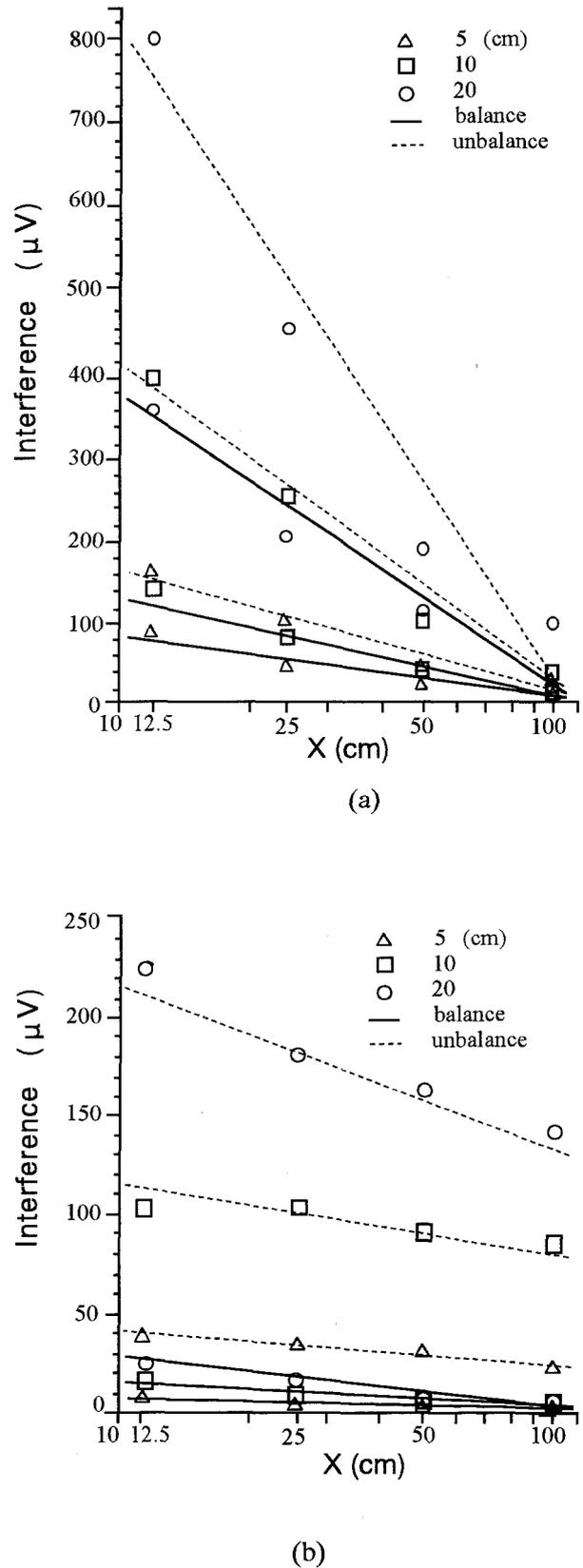
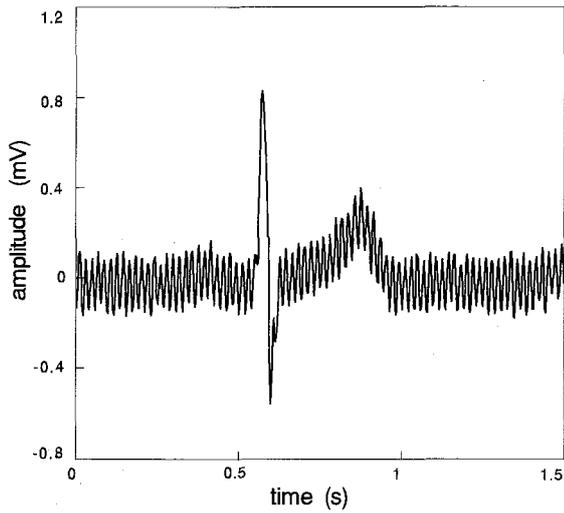
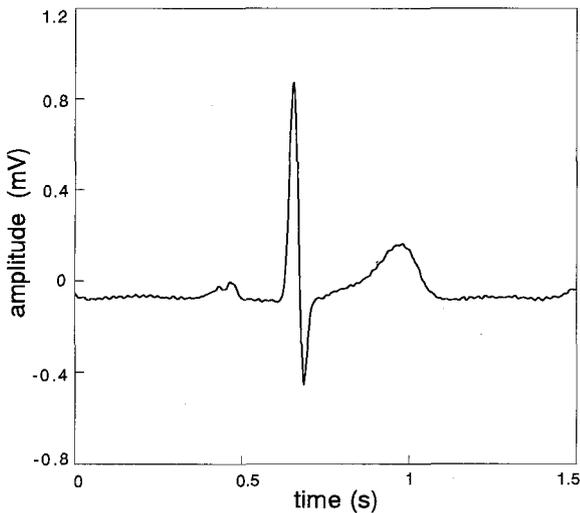


Fig. 5 Power-line interference for a model. (a) horizontal direction and (b) vertical direction.



(a)



(b)

Fig. 6 ECG signal recording with its interference and APC in vertical direction with skin-electrode impedance : (a) unbalance and (b) balance.

ing and abrading the electrode sites. Moreover, displacement currents, which are induced into leads, are reduced more if the leads are shielded^{8,9}. The simulation of displacement currents induced into the leads and the human body have been also collated to evaluate each relative contribution to total interference by using referenc-

ing technique⁹.

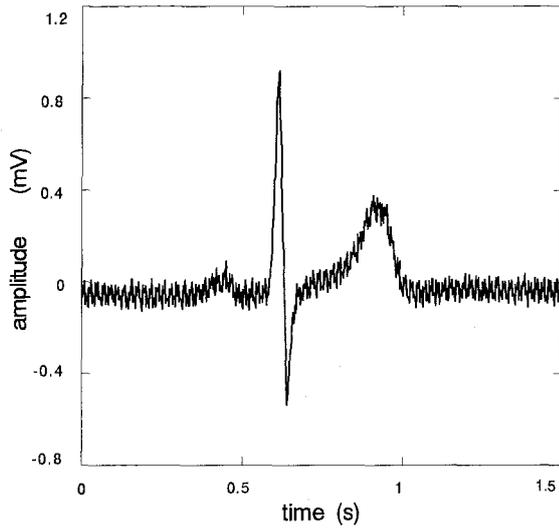
However, in this work we consider that displacement currents are not equal and impedances are unbalanced. In the next section, we show in detail the phenomenon of the interference by this displacement currents to a model, to a human body and to impedance balance.

1 A model

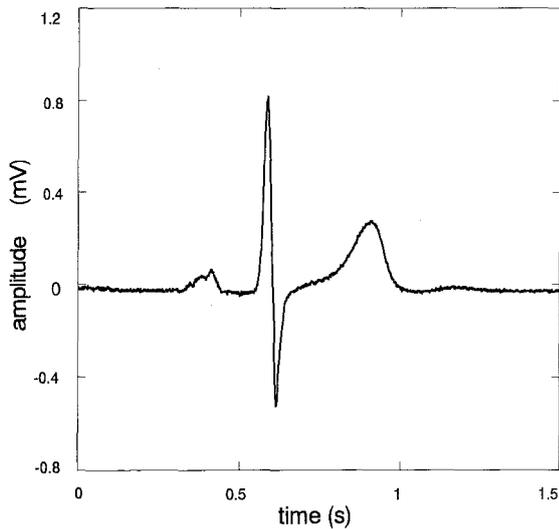
Fig. 5 shows the interference caused by displacement currents from APC into a model. In Fig. 5a, APC was adjusted to horizontal direction. This figure shows that there are significantly difference of interference between the use of impedance balance and unbalance. Interference is larger in conditions as follows : (a) APC is closer to the model ; (b) the length of unshielded leads are longer ; and (c) both of main resistors Z_1 and Z_2 , are unbalanced. These conditions are the same as discussed by other researchers^{2,9}. When APC is closer to the model, the displacement current is larger, because the displacement current is inversely proportional to the distance between APC and main resistors. This causes that the interference is larger.

In Fig. 5b, APC was adjusted to vertical direction. The interference remains smaller even though the main resistors are unbalanced. In this case displacement currents flow symmetrically from APC into a model. In the same way, the interference can be eliminated to be the smaller if the main resistors are balanced. This figure also shows that the interference is able to achieve to be smaller than $10 \mu\text{V}$ at the distance which is equal or more than 50 cm between APC and the model. Based on this experiment, it was shown that equation (2) is almost valid under many conditions. This phenomenon have not explained clearly by other researchers yet^{2,9}.

The experiment can be performed easily, if only APC is used as source of power-line without many sources of power-line in the environment of a model. Therefore by this modelling we are able to understand easily the interference phenomenon. In addition, this method can be applied to improve the quality in measurement of



(a)



(b)

Fig. 7 ECG signal recording with its interference. Skin-electrode impedances are controlled by using impedance balance controller : (a) unbalance and (b) balance.

biopotential signal especially in eliminating of interference from original signals.

2 Human body

ECG signal recording using a model is shown in Fig. 6. Fig. 6a shows that interference is very

large, about $100 \mu\text{V}$. This interference is caused by displacement currents in relation to the position of APC in horizontal direction and skin-electrodes are unbalanced. However, if APC is adequately moved to vertical direction, the interference can be eliminated to very small as about $10 \mu\text{V}$ as shown in Fig. 6b. This condition means that contribution of displacement currents from APC into a model are symmetry.

3 Impedance balance controller

Skin-electrode impedance value in right- and left-wrist during recording were about $28 \text{ k}\Omega$ and $18 \text{ k}\Omega$, respectively. First, we defined this condition as unbalance and the result shows that ECG signal with interference is about $80 \mu\text{V}$ as shown in Fig. 7a. Second, for balancing condition, we used skin-electrode impedance for right- and left-wrist which were about $149 \text{ k}\Omega$ and $184 \text{ k}\Omega$, respectively. This value is obtained by adjustment of trimpot.

In Fig. 7a, impedance in both skin-electrode and leads system must not be really the same, but both their potential balance are important to be considered. Although wave form of ECG signal recording is not enough smooth, we are able to reduce interference to about 1% of ECG signal normal or $10 \mu\text{V}$ as shown in Fig. 7b.

Impedance balance is important element for eliminating the interference. However, in actual situation, impedance balance is not perfect condition because two displacement currents are not always equal.

Conclusions

In this paper, we proposed a modelling of interface construction to consider power-line interference phenomenon in biopotential signal measurement system. Based on performance evaluation and experiment results, the following conclusions could be obtained.

1. We consider displacement currents as the main source of power-line interference which is coupled by capacitance from power-line to a subject and unshielded leads. Interference by this displacement currents depend on some factors

such as distance and position of the APC, length of unshielded leads, and skin-electrode impedances which are balance or unbalanced.

2. The interference can be eliminated if skin-electrode impedances are small or balance. However, interference is still large even though skin-electrode impedances are balanced. It was caused by the disagreement in two displacement currents. This case can be overcome by adjustment of APC in vertical direction because displacement currents are symmetry. Consequently, total interference will be very small or zero. We have applied this method to real ECG recording that interference can be eliminated to about $10 \mu\text{V}$.

3. Interference of power-lines is a complicated phenomenon. However, by applying this modeling we are able to simplify the problem so that the power-line interference phenomenon especially in biopotential signals measurement system is easily to understand.

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生体電気信号の計測システムへの電力線からの 誘導障害に関するインターフェイスモデル

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要 約

生体電気信号の測定における電力線からの誘導障害についての研究が多く報告されているが、この現象についての説明が十分なされていなかった。本研究では、この現象を簡単なインターフェイスモデルを用いて説明した。

誘導障害の原因として、電極の導線が作るループ内に発生する誘導起電力、システムの変位電流、生体アンプ内で発生する雑音等があげられる。本研究においては、電力線と導線との静電結合によってその間を流れる変位電流と被験者と電極間のインピーダンスに注目した。この変位電流による誘導は、いくつかの要素に依存している。それらは、・被験者と電力線との距離、・被験者に対する電力線の方向、・導線のシールドされていない部分の長さ、・被験者と電極間のインピーダンスである。

そこで、被験者と電力線との距離や導線のシールドされていない部分の長さなどを変化させて、心電図の測定を行った。被験者と電極間のインピーダンスを調整できるように、可変抵抗を用いた RC 並列回路をそれぞれの導線に直列に接続した。また、導線のループに発生する誘導起電力をできるだけ小さくするために、導線を互いに擦ってループ面積を小さくした。

誘導雑音は、以下の場合に大きくなった。・電力線の距離が近い。・導線のシールドされていない部分が長い。・被験者と電極間のインピーダンスが大きく、不均衡である。また、被験者と電極間のインピーダンスを等しくした場合でも、誘導雑音が観測された。電力線の位置により各導線と電力線との静電結合状態が異なり、各導線に流れる変位電流が等しくないことが誘導雑音の原因であることを示した。

本研究では被験者と電極間のインピーダンスおよび変位電流による誘導雑音の影響について検討した。この現象の理解は誘導障害の除去に大変有益なものである。

キーワード：電力線配置, 生体電気信号, 変位電流, モデル, 誘導障害

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