The Electrocardiographic Leads for Telemetry as Evaluated from View Point of the Transfer Impedance Vector

Yoshihisa NAGATA, M.D.

SUMMARY

(1) From the torso model experiments, the measurements of the transfer impedance vectors were carried out for the conventional 12 leads, Frank's lead system and the following 6 different leads commonly used for the ECG-telemetry such as $V_{5R}-V_1 \sim V_9$ leads, EEP leads, C_5-M lead, L_1-ST_1 and L_1-TH_1 lead, when the current dipole was placed in turn at 27 points within the space occupied by the heart in the human torso model filled with electrolyte solution. The transfer impedance vectors for all leads above-mentioned were compared to each other.

(2) $V_{5R}-V_1 \sim V_9$ leads can be used for the ECG-telemetry, as the equivalent to the precordial leads $V_1 \sim V_9$. C_5-M , EEP- C_5 and $V_{5R}-V_5$ lead could be equivalent to the precordial lead V_5 , and L_1-ST_1 and L_1-TH_1 lead were equivalent to the augmented unipolar limb lead aV_F .

(3) Taking into account of the experimental result, the number of electrodes applicable and the possibility to eliminate the interference of muscle potential, C_5-M , $V_{5R}-V_5$ and L_1-TH_1 lead can be considered to be the most sensitive leads for detecting coronary artery disease in latent form.

Additional Indexing Words:

Cardiac electromotive force Lead vector Heart vector Human torso model Artificial current dipole

THE bio-medical telemetry, which is a means of the recording the important electrophysiological informations of the human subjects during physical exercise or in remote, is applied largely in the field of medicine. Many reports upon the practical application of electrocardiographic telemetry have been presented, but the reports on the basic investigation have been very few and further investigation will be necessary for the development of the method and technique in its telemetry. The one of the main purposes of the ECG-telemetry is to find out any change of the electrical activity of the heart during the physical exercise of the human subjects. Therefore, it is necessary for the ECG-telemetry that the electrodes applied on the body

From the Division of Circulation and Respiration, the Research Institute of Environmental Medicine, Nagoya University, Nagoya.

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surface should be less in number and the lead system should possess lesser degree of signal-to-noise ratio if technically possible, namely the avoidance of interference by muscle potentials and furthermore it is hoped that any lead system can more faithfully record the ST-T changes in electrocardiogram. The purpose of this investigation was to evaluate the superiority and validity among the 6 different lead systems currently used for the ECG-telemetering, based on the results derived from the analysis of the transfer impedance vectors.

THEORETICAL PRINCIPLE

Burger and van Milaan¹⁾ have proposed that the potential difference appearing on any given electrocardiographic lead could be expressed by the scalar product of the heart vector ($\vec{H}$) and its relevant lead vector ($\vec{L}$). Schmitt²⁾ has proposed the similar concept, but he has used his term as the transfer impedance vector for the analog of the lead vector. Therefore, it could be considered that the lead vector is essentially same as the transfer impedance vector in the theoretical background.

The unit cardiac electromotive force (E.M.F.) of the infinitesimal small area located at the boundary between the excited and unexcited myocardium is supposed to be represented by equivalent current dipole and this unit of E.M.F. is expressed as $\vec{H}_i$ in terms of vector quantity, and this E.M.F. vector ($\vec{H}_i$) is expressed as 3 vectorial components on X, Y and Z 3 rectangular orthogonal co-ordinates, resulting their magnitudes and directions to be H_x^i , H_y^i and H_z^i respectively.

The transfer impedance vector, electrically measured between the location of a given current dipole and arbitrary lead points, is defined as $\vec{L}_i$ in terms of vector quantity, and the components of its vector are denoted as L_x^i , L_y^i and L_z^i in the similar fashion as the E.M.F. vector is defined.

In this situation above-mentioned, an electrical potential difference (V_i) at a given lead point based upon such single E.M.F. of the unit area will be expressed as follows:

$$V_i = \vec{H}_i \cdot \vec{L}_i = H_x^i \cdot L_x^i + H_y^i \cdot L_y^i + H_z^i \cdot L_z^i$$

Based on the electrical principle of superposition, the electrical potential difference appearing in a given lead is obtained by summing up all of the individual electrical potential difference deriving from the every elementary unit area.

Namely, it is expressed as follows:

$$\sum V_i = \sum \vec{H}_i \cdot \vec{L}_i = \sum (H_x^i \cdot L_x^i + H_y^i \cdot L_y^i + H_z^i \cdot L_z^i)$$

Thereupon, in case that if the heart vector (the summation of all of the E.M.F. vector) will possess some direction and magnitude, the potential difference appearing on any given lead will be determined by the direction and magnitude of the transfer impedance vector.

It can be rationally conceivable that the identical electrocardiographic patterns could be recorded, when 2 different lead systems possess the same lead vector each other, even in the case of different locations of electrodes anatomically on the body surface.

On the basis of the above stated facts, the suitability of any lead systems useful for the ECG-telemetering can be evaluated theoretically from the analysis of the transfer impedance vector.

METHOD

1. *The measurements of the transfer impedance vectors were carried out for the following lead systems*

- i) Frank's X, Y and Z lead
- ii) Unipolar limb lead (V_R , V_L and V_F)
- iii) Precordial lead (V_1 to V_6)
- iv) Ear-Ensiform-Precordial (E-E-P) lead proposed by LaDue et al.³⁾

The central terminal composed from 3 electrodes located at the right ear, the ensiform process and any point on precordium, based on the similar idea of Wilson's central terminal. The potential difference was obtained between this central terminal and each of the exploring precordial lead points C_4 , C_5 and C_6 .

- v) Nehb's "A", "D" and "J" lead⁴⁾

"A" lead in bipolar nature consists of 1 electrode for negative pole placed at the second intercostal space at the junction of the right sternal border and the other for positive pole placed at the point of cardiac apex beat on the thorax, and "D" lead between the negative pole at the second intercostal space at the junction of the right sternal border and positive pole at the point on the posterior axillary line at the same level of apex beat, and "J" lead between the negative pole at the point on the posterior axillary line at the same level of apex beat and the positive pole at the point of apex beat.

- vi) C_5 -M lead used by Craige et al.⁵⁾ and Blackburn et al.⁶⁾

This lead consists of the negative pole at the upper margin of manubrium sterni and of the positive pole at the point on the anterior axillary line at the level of the fifth intercostal space.

- vii) V_{5R} - V_1 ~ V_9 (C_{5R} - C_1 ~ C_9) leads used by Gilson et al.,⁷⁾ Bellet et al.⁸⁾ and Takagi et al.¹⁰⁾

These leads consist of 1 electrode for negative pole at the point on the right anterior axillary line on the level of the fifth intercostal space and of the other for positive pole at each of the left hemithoracic lead points V_1 to V_9 .

- viii) L_1 - ST_1 and L_1 - TH_1 lead proposed by Kobayashi et al.¹¹⁾

These leads consist of 1 electrode placed at the left side of the first lumbar vertebra and of the other placed at the point on the first intercostal space at the junction of the left sternal border, or at the point on the left side of the first thoracic vertebra respectively.

2. *The measurement of the transfer impedance vector (Fig. 1)*

The human torso model previously reported¹²⁾ was filled with 0.1% saline solution with its conductivity of 383 ohm-cm. at 25°C. The artificial current dipole was inserted into the torso model and placed in turn at 27 points, which sufficiently covered the space usually occupied by the heart within the human torso model, as the orthogonal direction (X, Y and Z axes) of the dipole could coincide with the anatomical orthogonality of the torso model. Then, the dipole was energized with a unit strength current of 4.0 mA, in sinusoidal wave at 100 Hz per sec. through the

Fig. 1. Schematic illustration of experimental set-up.

A: human torso model	B: three directional current dipole
C: dipole-assembly	D: three way cathetometer for setting the dipole at the desired location
E: dipole location within the human torso model	

oscillator (Hewlett-Packard model 204B) in 3 orthogonal directions in turn. Then, at every dipole location, the electrical potential difference was measured between the relevant corresponding lead points, and these measured values were considered to be equivalent to the magnitudes and directions of the transfer impedance vectors. This measurement was carried out for each of the ECG-telemetering leads above mentioned and of Frank lead system and of the conventional 12 lead systems. In this study, the polarity of the reference frame X, Y and Z was defined as follows: the left being positive on the left-to-right direction, the caudal direction being positive on the cephalo-caudal direction and the anterior direction being positive on the anteroposterior direction in respect to the anatomical rectangular 3 directions of the human torso model.

RESULTS

The measurements for the transfer impedance vector were carried out, when the artificial current dipole was placed at each of 27 points in turn.

The representative case, in which the measurement was done when the dipole was placed at the ventricular center, was illustrated in Fig. 2 for the convenience of better understanding of the results obtained from the analysis of the transfer impedance vector of each of all telemetering lead systems under investigation.

The lead systems, which would possess the fairly satisfactory magnitude of the transfer impedance vector, were C_5 -M, EEP- C_5 , Nehb-"A" and V_{5R} -

V_4, V_5, V_6 for the X-component, C_5-M , Nehb-"A" and "J", L_1-ST_1 , L_1-TH_1 for the Y-component, EEP- C_4 , Nehb-"J", $V_{5R}-V_2$, V_3 , V_4 for the Z-component (Fig. 2).

The magnitudes of 3 orthogonal components (X, Y and Z) of the transfer impedance vectors were compared each other, when the dipole was placed at each of 26 dipole locations in turn, beside at the ventricular center. These results were very similar to those obtained in the case that the dipole was set at the ventricular center.

The magnitudes of the transfer impedance vectors at several dipole location including the ventricular center in turn, were compared each other. Comparative analysis between the lead $V_{5R}-V_1 \sim V_6$ and the precordial lead V_1 to V_6 showed that the magnitudes of 3 orthogonal components (X, Y and Z axes) of the transfer impedance vector were in good resemblance each other, as may be seen in Fig. 2 and 3.

The magnitudes and directions of vectorial sum from X and Z components of the transfer impedance vector were illustrated for the EEP- C_4 , C_5 and C_6 lead and for the precordial lead V_4, V_5 and V_6 . It was very interesting to note that these leads were very similar to each other in respect to their magnitudes and directions (Fig. 4).

All 3 vector components (X, Y and Z) of the transfer impedance vector

Fig. 2. The magnitudes of three orthogonal components (X, Y and Z) of the transfer impedance vectors for various leads, when the dipole was placed at the ventricular center. The diagram in the left side show the values for the various leads commonly used for recording the resting-ECG, whereas the diagram in the right shows the values for the various leads useful for the ECG-telemetering. The polarity in each diagram was as follows: the right being positive and the left being negative in each component.

Fig. 3. The magnitudes and directions are illustrated for X and Z components of transfer impedance vectors measured for the precordial lead V_2 and V_3 shown by interrupted line vectors, the lead $V_{5R}-V_2$ and V_3 by solid line vectors at the right in this figure, the precordial lead V_4, V_5 and V_6 shown by interrupted line vectors, and the lead $V_{5R}-V_4, V_5$ and V_6 shown by solid line vectors at the five spatial loci (indicated by black spots) on the horizontal plane across the ventricular center. The convention was given only for the vectors measured at the ventricular center.

Fig. 4. Transfer impedance vectors measured for the precordial lead V_4, V_5 and V_6 shown by interrupted line vectors and the EEP- C_4, C_5 and C_6 shown by solid line vectors. The same conventions used as shown in Fig. 3.

Fig. 5. The frontal components (X and Y) and the horizontal components (X and Z) of transfer impedance vectors measured for the precordial lead V_5 and for the lead C_5 -M, when the dipole was placed in turn at five different locations on the frontal plane across the ventricular center (at the left in this figure) and on the horizontal plane across the ventricular center (at the right in this figure).

Fig. 6 (a). The frontal (X and Y) and sagittal (Y and Z) components of transfer impedance vectors of the unipolar lead V_F and the lead L_1 - ST_1 when the dipole was placed in turn at five different locations including ventricular center on the frontal plane (at the left in the figure) and on the left sagittal plane (at the right in the figure). The solid line vector indicates the lead L_1 - ST_1 , whereas the interrupted line vector indicates the unipolar lead V_F . The magnitudes and directions of these vectors were compared each other.

Fig. 6 (b). The frontal (X and Y) and sagittal (Y and Z) components of transfer impedance vectors of the unipolar lead V_F and the lead L_1-ST_1 when the dipole was placed in turn at five different locations including the point of the ventricular center on the frontal plane (at the left in the figure) and on the left sagittal plane (at the right in the figure). The solid line vector indicates the lead L_1-TH_1 , whereas the interrupted line vector indicates the unipolar lead V_F .

for C_5-M lead were in better accordance to those for the precordial V_5 lead, as compared with the V_5R-V_5 lead and $EEP-C_5$ lead, as may be seen in Fig. 5.

The spatial vector composed by the rule of parallelogram from these X, Y and Z components of the transfer impedance vector measured for Nehb-"A" lead was directed to the left inferior anteriorly, in Nehb-"D" lead directed to the left inferior posteriorly, in Nehb-"J" lead directed to the inferior anteriorly, and all of these leads were noted to possess the fairly satisfactory magnitudes of the transfer impedance vectors.

The vectorial sum calculated from Y and Z components of the transfer impedance vector measured for L_1-ST_1 and L_1-TH_1 lead were approximately parallel to the anatomical cephalo-caudal direction of the torso model (Y-axis) and to the direction of Y-component in the lead V_F , as shown in Fig. 6(a) and (b).

All results presented above were derived from the analysis of the transfer impedance vectors when the dipole was placed, in turn, at several locations including the ventricular center within the space of the torso model occupied by the heart. However, further studies showed that almost similar results were also obtained when the dipole was displaced at other locations in the vicinity to

the space occupied by the heart.

DISCUSSION

The post-exercise electrocardiogram to evaluate coronary reserve, proposed by Master,^{13), 14)} has been used as the important auxiliary aid to the detection of coronary artery disease, and this method is to record the ECG after the actual period of exercise from the subject resuming in resting supine position. Since the validity of using this post-exercise electrocardiogram has been recognized in the field of cardiology, the further important advent has been made by using the miniature radio-electronics; the radio-electrocardiography proposed by Holter¹⁵⁾ in 1957, provided a practical method of recording the dynamic ECG changes during the actual period of exercise.

Takahashi and Iwatsuka et al.¹⁶⁾ investigated the diagnostic accuracy of the post-exercise ECG and the dynamic-exercise ECG (ECG taken during actual period of exercise) for detection of the ST segment depression in ischemic heart disease, and they concluded that the post-exercise ECG was more useful in that clinical aspect.

On the other hand, Kobayashi et al.¹¹⁾ investigated to find the time relationship in which the maximal change of ST-T deviation appears during and after actual period of exercise, by taking the dynamic-exercise ECG and the post-exercise ECG recorded by the V_{5R} - V_5 lead system, and they found that the detection ratio of positive tracing was almost equal; 50% in the postexercise and the dynamic-exercise ECG_s in the subject-group displaying the normal resting ECG, however, its ratio is much higher in the dynamic-exercise ECG in the subject-group displaying the resting ECG to be abnormal. The similar results were reported by LaDue et al.^{3), 17)} and Bellet et al.^{8), 9)}

From the results above-mentioned, it is rationally suggested that ECG-telemetering could be useful even in the case of the Master's two step test, for the early detection of ischemic heart disease.

For the clinical application of telemetering ECG practically, any lead, of which the electrodes could be firmly contacted to the skin, should be chosen in order to eliminate the muscle potential. For the elimination of muscle potential, it is necessary that the electrode should be applied to the body surface where the body motion is minimal, and should not be applied to any part on all 4 extremities which may provide the interference of muscle potential to the ECG tracing.

Therefore, 6 different lead systems for the ECG-telemetering, in which the electrode positions were restricted to the thoracic surface and forehead, were investigated in the present study.

Regardless of wire-transmission or wireless-transmission of ECG-signal, the practical value of ECG-telemetry may be evaluated by the possibilities whether ECG-signal can be recorded during actual period of exercise or not, whether the monitoring of ECG-signal supplied from remote distance can be performed for rather long period of time or not. In such condition, number of leads should be limited to 1 or 2 bipolar leads in maximum, and therefore, these leads are naturally required to possess the ability to record the necessary and sufficient parametric informations in ECG-signal.

On the other hand, it is very useful and convenient for the electrocardiographic diagnosis that if the pattern recorded by any lead of ECG-telemetry will closely resemble in configuration to those of conventional 12 leads, and moreover much convenient, if these leads of the ECG-telemetry will possess the excellent capability and sensitivity to register ST-T change more precisely in the case of coronary insufficiency.

From the above-mentioned reasons, it can be advantageous that the magnitude and direction of the transfer impedance vector of any lead for the ECG-telemetry will closely resemble to those of ST-vector¹⁸⁾ in general, and to those of conventional 12 leads, for example V_L , V_F and the precordial lead V_1 to V_6 which have been known to be sensitive in registering the ST-T change in resting ECG in the case of coronary artery disease.

As already shown in the part of the result, the precordial leads V_1 to V_6 were noted to be closely resembled to the leads V_{5R} - V_1 to V_6 for telemetry use, when these 2 different lead systems were compared to each other in respect to the magnitudes and directions of their transfer impedance vectors. It was reported also by Kobayashi et al.¹¹⁾ that these lead systems were in good accordance each other in respect to the pattern and the amplitude of electrocardiogram, as based on the result of analysis on actually recorded ECGs in clinical materials.

Upon the comparison of the precordial leads V_4 , V_5 and V_6 with EEP- C_4 , C_5 and C_6 in respect to the transfer impedance vector, the EEP lead system showed the better resemblance than V_{5R} - V_4 , V_5 and V_6 , although EEP lead system has some disadvantage that this system needs more electrodes in number than V_{5R} - V_4 , V_5 and V_6 .

LaDue et al.³⁾ pointed out one of the advantageous aspects that the EEP-central terminal would show approximately same reference potential to the Wilson's central terminal, thus the EEP- C_4 , C_5 and C_6 system could produce the ECG pattern very closely resembling in configuration to those recorded by the precordial leads V_4 , V_5 and V_6 . This point was also verified from the view point of the transfer impedance vector in the present study.

The transfer impedance vector for C_5 -M lead system was directed to the

left inferior more or less anteriorly, and was in better accordance with that for the precordial lead V_5 , than that for the EEP- C_5 .

Blackburn et al.⁶⁾ proposed that EEP- C_5 lead and C_5 -M lead system were the most sensitive to ST-T change, based upon the result of investigation in which the dynamic-exercise and post-exercise ECGs recorded by several different lead systems for telemetering were compared in respect to the capability to record ST-T change.

In the transfer impedance vectors for Nehb lead systems, its X and Y components were noted to possess the fairly satisfactory magnitude in "A" and "D" lead, and its Y and Z components in "J" lead, thus these lead systems were considered to be capable to register rather selectively the change of electromotive force occurring at the left-antero-inferior part of the heart.

The magnitudes of the transfer impedance vectors measured for L_1 -ST₁, L_1 -TH₁ lead were greater than that of lead V_F , and that of L_1 -TH₁ lead was slightly larger than that of L_1 -ST₁ lead. The direction of the transfer impedance vector measured for L_1 -TH₁ lead was closer to that for V_F than that for L_1 -ST₁ lead. From the viewpoint of the transfer impedance vector, the ECG patterns recorded by both L_1 -ST₁ and L_1 -TH₁ lead were considered to be similar to that of lead V_F , and L_1 -TH₁ lead is thought to be superior to L_1 -ST₁ lead. This superiority of L_1 -TH₁ lead was also reported by Kobayashi et al.,¹¹⁾ as based on the result of analysis on the pattern and amplitude of QRS complex actually recorded from clinical materials.

Yamada et al.^{19), 20)} stated that 3 abridged ECG leads (aV_F , V_1 and V_5) were quite adequate and accurate theoretically and clinically for the electrocardiographic screening tests in population mass survey. Therefore, it can be quite convenient if any pattern recorded by some leads for ECG-telemetering will resemble in configuration to those recorded by 3 abridged ECG leads. Especially, it has been known that the effect of physical exercise upon ECG was mainly due to the anoxic change occurring in the left ventricle, when the physical exercise was given to the subject with coronary artery disease. The precordial lead V_5 , and the augmented unipolar limb lead aV_F may register the change of the electromotive force occurring at the left anterior part of the heart and at the infero-posterior part of the heart respectively. Therefore, it may be suitable for ECG-telemetering that any lead, in which the pattern can resemble to those recorded by V_5 and aV_F lead, can be obtained.

From the above-mentioned reasons, it can be suitable, appropriate and recommended to use V_{5R} - V_5 , EEP- C_5 , C_5 -M and L_1 -TH₁ lead for the ECG-telemetering, which were capable to record the patterns resembling in configuration to that of the precordial lead V_5 and lead V_F .

When the condition restricted to only one lead applicable for ECG-tele-

metering, it can be thought that C₅-M lead is the most suitable, because of less electrodes used in number and lesser degree of interference of muscle potential. It is also advantageous for easily making diagnosis of coronary artery disease, because this lead will be able to record the greatest degree of ST-T deviation.

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