A novel method of synthesizing a 12-lead electrocardiogram (ECG), with practically identical waveforms to the standard 12-lead ECG (Stn-ECG) from 3-channel ECGs recorded by Holter monitoring has been developed.

**Methods and Results** The study group comprised 16 healthy individuals and 13 patients with abnormal ECGs. The bipolar eV1, eV5 and eVF leads were recorded using digital Holter monitoring and nine Syn-ECGs, corresponding to each lead of the Stn-ECG, were synthesized. The 9 ECGs consisted of a theoretical Syn-ECG and 8 Syn-ECGs positioned around the theoretical Syn-ECG at 3 cm intervals on the Frank’s image surface. Of the 9 ECGs, the Syn-ECG with the maximum product of the cross-correlation coefficient of the QRS wave and that of the T wave, was automatically selected as the optimal Syn-ECG. The amplitude data from the QRS wave, R wave, T wave, and ST level, and also the amplitude ratio of the R wave, T wave to the QRS wave, were significantly well correlated between the Syn-ECG and Stn-ECG.

**Conclusions** A practically identical ECG morphology, comparable with a Stn-ECG, was successfully created using this system. (*Circ J* 2004; 68: 751–756)

**Key Words:** eVn leads; Frank’s image surface; Holter monitoring; Lead vector; Synthesized 12-lead ECG

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**Background** A new system of synthesizing a 12-lead electrocardiogram (Syn-ECG) with practically identical waveforms to the standard 12-lead ECG (Stn-ECG) from 3-channel ECGs recorded by Holter monitoring has been developed.

**Methods**

**Subjects**

The subjects consisted of 29 individuals: 13 consecutive subjects who had had an ECG recorded with the present system (12 males, 1 female, mean age 64±10 years, range: 39–74) that included 7 with myocardial infarctions (4 anterior wall and 3 inferior wall), 5 with complete bundle branch block (BBB) (4 right BBB and 1 left BBB) and 1 with atrial fibrillation, and 16 normal volunteers (mean age 31±5 years, range: 23–41).

**ECG Recording**

To record the synthesized ECG (Syn-ECG), 5 electrodes were placed on the body surface, with the anode consisting of the V1 and V5 positions, and the point of intersection

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![Fig 1. Position of the electrodes used in the Holter monitoring in this study.](image)
between a perpendicular line to \( V_4 \) and a horizontal line to
the navel, the cathode as \( V_{7R} \), and an additional electrode
as the ground (Fig 1). These bipolar leads were named the
\( eV_1, eV_5 \) and \( eVF \) leads, respectively. The \( eV_n \) leads were
developed to record practically identical waveforms to the
unipolar chest leads with a bipolar lead. The individual
electromotive forces of \( eV_1, eV_5 \) and \( eVF \) were substituted into
the simultaneous equation, shown below, in order to solve
the X, Y and Z factors for the electromotive force vector.

\[
\begin{align*}
eV_1 &= -19X - 47Y - 94Z \\
eV_5 &= 195X - 7Y - 10Z \\
eVF &= 51X + 111Y - 27Z
\end{align*}
\]

Consequently, the lead vectors for each ECG of the Stn-
ECG were calculated and created from the generator.

Automatic Correction of the Individuality of the Lead
Vector

The individual lead vectors were obtained by following
method. Nine Syn-ECGs corresponding to each lead of the
Stn-ECG were synthesized. The 9 ECGs consisted of a
theoretical Syn-ECG and 8 Syn-ECGs positioned around
the theoretical Syn-ECG at 3 cm intervals on the Frank’s
image surface. A Syn-ECG representing the Stn-ECG,
which was recorded before the start of the Holter monitor-
ing, was automatically selected from the 9 Syn-ECGs. A
cross-correlation algorithm was used for creating Syn-
ECG morphologically close to Stn-ECG. The basis of the
selection was as follows. The cross-correlation function
between the QRS wave and T wave of the Stn-ECG and
Syn-ECG was calculated using a computer, and the maxi-
imum value was defined as the cross-correlation coefficient.
The Syn-ECG with the maximum product of the cross-cor-
relation coefficient of the QRS wave and T wave
was automatically selected by a computer algorithm as the
optimal Syn-ECG (Fig 2).

Comparison of the Stn-ECG to the Syn-ECG

The QRS wave amplitude (peak to peak), R wave ampli-
tude, T wave amplitude and ST level at 80 ms after the J
point (ST80) were measured in all leads. The QRS wave
amplitude, R wave amplitude, T wave amplitude, ST80
Fig 4. Relationship between the R wave amplitude determined from the synthesized ECG and standard 12-lead ECG.

Fig 5. Relationship between the T wave amplitude determined from the synthesized ECG and standard 12-lead ECG.

Fig 6. Relationship between the ST80 determined from the synthesized ECG and standard 12-lead ECG.

Fig 7. Relationship between the R wave amplitude/QRS wave amplitude ratios determined from the synthesized ECG and standard 12-lead ECG.

Fig 8. Relationship between the T wave amplitude/QRS wave amplitude ratios determined from the synthesized ECG and standard 12-lead ECG.
were compared between the Stn-ECG and Syn-ECG. The ratios of the R wave and T wave amplitudes to the QRS amplitude were compared between the Stn-ECG and Syn-ECG. The above mentioned amplitudes and ratios are discussed using the correlation coefficient.

Statistical Analysis

The Pearson's correlation coefficient was used for comparisons, and a p-value <0.05 was defined as significant. The data were analyzed using StatView version 5.0 software (SAS Institute Inc, Cary, NC, USA). Each value represents the mean value ± the standard deviation (SD).
Results

QRS Wave Amplitude, R Wave Amplitude, T Wave Amplitude and ST80

The correlations between the Syn-ECG and Stn-ECG in regard to the QRS wave amplitude, R wave amplitude, T wave amplitude and ST80 are shown in Figs 3–6. The correlation coefficient observed between the Syn-ECG and Stn-ECG in regard to the QRS wave amplitude was $r=0.98$ at $y=0.97x-4.7$ ($p<0.001$), the R wave amplitude was $r=0.96$ at $y=0.95x-0.43$ ($p<0.001$), the T wave amplitude was $r=0.92$ at $y=0.92x+1.37$ ($p<0.001$), and the ST80 was $r=0.97$ at $y=0.99x+0.01$ ($p<0.001$), respectively.

R Wave and T Wave Amplitude Ratios to the QRS Wave Amplitude

The correlations between the Syn-ECG and Stn-ECG in regard to the R wave and T wave amplitude ratios are shown in Figs 7 and 8. The correlation coefficient observed between the Syn-ECG and Stn-ECG in regard to the R wave amplitude was $r=0.96$ at $y=0.90x+0.05$ ($p<0.001$), and that for the T wave amplitude ratio was $r=0.90$ at $y=0.89x+0.04$ ($p<0.001$).

Case Reports

The Syn-ECG from an actual case (healthy volunteer, 27-year-old male) is shown in Fig 9. The Syn-ECG has practically identical waveforms to the Stn-ECG. In Fig 10, ECGs from a case with complete RBBB (70-year-old male), and in Fig 11 those from a case with previous myocardial infarction (61-year-old male) are shown. In both cases, Syn-ECGs closely resembling the Stn-ECGs were created, although a slight difference in T wave polarity can be identified in the V6 lead in Fig 11.

Discussion

Detection Rate of Ischemic ST Segment Deviation by the Discrimination of the Leads

In 1985, the American Heart Association recommended V1-like and V5-like leads for Holter monitoring and these are the leads usually used in Japan. Further, the accuracy of the detection of ischemic ST segment depression is believed to be 85–90% in the V5-like lead. However, if the V3–6 leads are used, that accuracy increases (89%), and furthermore, if leads II, aVR, and V3–6 are used, that accuracy increases more (100%). For ischemic ST segment elevation, the accuracy is high in the V2–3 leads for left anterior descending artery spasm, and in leads III and aVF for right coronary artery spasm. Furthermore, ST segment elevation accompanied by a heart attack can be detected with leads III or V3 in 98% (333 of 339 patients) of the patients with vasospastic angina pectoris. In order to increase the accuracy of the detection of ischemic ST segment depression with Holter monitoring, we developed a novel method of synthesizing 12-lead ECG waveforms that are practically identical to those of the Stn-ECG lead from a 3-channel ECG signal with Holter monitoring.

Procedure to Record More ECG Leads Using a Holter Monitoring System With Limited Recording Leads

Holter monitoring usually has a recorder capable of recording 2 or 3 ECG leads. Two methods for recording ECG information from more leads have been investigated. One method is to change the recording leads by using an adapter, making it possible to record either 3-channels, 9-channels, 10-channels, or 30-channels; however, continuous ECG recordings are lost. Continuous ECG recordings are useful for differentiating ischemic ST segment depression from the ST segment deviation related to postural changes. The other method is to synthesize the signals using Frank.
It is possible to calculate the lead vector from the Frank's image surface leads, but it is a theoretical value that is experimentally produced using the torso model with single dipoles. Therefore, the uniqueness of the patient's physique, position of the heart and conductance volume (thorax, lungs, blood flow, skin, etc) are thought to affect the difference between the actual and theoretical values of the lead vectors. Furthermore, because the Frank's image surface leads are a theory based on a single dipole, this method is thought to be difficult to determine in those patients with BBB, Wolff-Parkinson-White syndrome, etc. Accordingly, an individual correction of the lead vector was needed. Dower corrected the lead vector, which corresponded to arm lead positions, in one using leads from the lower intercostal spaces. Consequently, it was observed that the P wave, T wave and R/S ratio were incompatible. The reason for the unsuccessful result of this method was thought to be related to having used a fixed lead vector. Accordingly, we developed a method to correct the individual lead vectors that resulted in successfully synthesizing practically identical ECG waveforms as those actually recorded by the 12-lead ECG. However, it was troublesome to have to calculate and establish individual lead vectors. Thus in the present study, we developed an algorithm that automatically corrected for the individuality of the lead vectors, using the cross-correlation coefficient as previously described. Consequently, the Syn-ECG waveforms corresponded closely to the Stn-ECG waveforms in both the healthy volunteers and patients with abnormal ECG waveforms.

Clinical Application of Syn-ECG on the Holter Monitoring System

Using lots of electrodes causes both discomfort during the recording and artifact on the ECG recordings. Thus we adopted a 3-channel recording method using bipolar chest leads equivalent to the unipolar chest leads (eVn leads) developed by Nakazawa. The eV1 lead is a bipolar lead recorded from a unipolar lead position (anode) and a position with an amplitude close to zero (cathode). This cathode is verified to have an amplitude close to zero without any effects from the individuality of the lead vectors. In particular, the ECG recorded from the eV1 lead corresponded well to the ECG recorded by the unipolar lead. Furthermore, in order to calculate the X and Z components of the lead vector, the eV1 and eV5 leads were used, and for the Y component, the eVF lead was used. For clinical Holter ECG analysis, the eV1 and eV5 leads are convenient. It will be very useful to perform Syn-ECG synthesis with this system for evaluation of ischemic ST change or ventricular arrhythmia morphology analysis.

Study Limitation

This study was preliminary investigation aiming to confirm the possibility of clinical application. Further investigation of its clinical usefulness will be needed, with evaluation of cases with ischemic ST changes or with ventricular ectopy.

Conclusion

We attempted to synthesize a 12-lead ECG, equivalent to the Stn-ECG, from the 3-channel eVn leads used in the Holter monitoring system. This novel system consisted of a lead vector calculation system and automatic correction for the individuality of the lead vector. Consequently, a practically identical ECG morphology, comparable with the Stn-ECG, was successfully created.

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