공학석사 학위논문

Reconstruction and Validation of the 12-Lead Electrocardiogram from 3-lead Patch-type Device

패치형 3-리드 심전도 장치를 통해 재구축한
12-유도 심전도의 임상적 유용성에 대한 연구

2018년 1월

서울대학교 대학원

협동과정 바이오엔지니어링전공

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The Graduate School Seoul National University

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Abstract

Reconstruction and Validation of the 12-Lead Electrocardiogram from 3-lead Patch-type Device

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The 12-lead electrocardiogram (ECG) is a vital diagnostic tool for cardiologists. A conventional 12-lead system is desirable to obtain full information from ECG, as different kinds of information can be obtained from different locations of leads. The standard 12-lead system requires 10 electrodes to be attached on a wide bare area of the human body. However, to be applied in a mobile system, a reduced number of electrodes is mandatory; in addition, lead positions should be close enough to be put in a patch system. For these reasons, we propose the 3-lead patch-type ECG device. With the signals obtained from the device, we synthesized 12-lead ECG by personal transformation and by universal transformation, equation that was established in 15 normal subjects.

These reconstructed ECGs were compared with standard 12-lead ECG. Measurements of normal parameters in standard, personal and universal transformation ECG were compared in 10 normal subjects. The total QRS voltage in universal

transformation was significantly lower than that in standard ECG ($p<0.04$). No statistically significant differences were observed among the normal parameters except in the case of the total QRS voltage.

The diagnostic sensitivity and specificity of personalized and universal transformation ECG were tested in 38 patients with pathologic findings in ECG (LVH: 14, wide QRS (≥ 120 ms): 6, pathologic Q : 6, ST elevation : 7, ST depression : 10, T inversions: 9). Both personalized and universal transformation ECG are sensitive and specific in the detection of the alteration in the direction of electric vectors as pathologic Q and T inversions, but are insensitive in the detection of small changes in the magnitude of electric vectors as ST changes. Personalized and universal transformation ECG were sensitive in detecting wide QRS complex; however, there were false positive cases with specificity of 77% and 79%, respectively.

Reconstruction of 12-lead ECG using a 3-lead patch-type device is feasible, valid in the measurements of normal parameters and can provide additional information compared to the single lead-ECG. However, further study is needed to increase the sensitivity of detecting ST changes and to overcome the problem of false positive wide QRS complexes.

Keyword: Patch-type device, synthesized ECG, Pathologic ECG

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1. Introduction

1.1. Clinical importance of ECG and ECG monitoring

Ever since Williem Einthoven, a Dutch doctor and physiologist first invented ECG in 1903 [1], it has been playing a vital diagnostic role in cardiology. ECG is the electrical activity generated by the human heart, that is measured by an array of electrodes placed on the body surface. The configuration of CG represents atrial depolarization (P wave), time delay between atrial depolarization and ventricular conduction (PR interval), ventricular depolarization (QRS complex), and ventricular repolarization (T wave) and, for the convenience of designation, names have been given to each of the waves and intervals[2, 3]. (Figure 1)

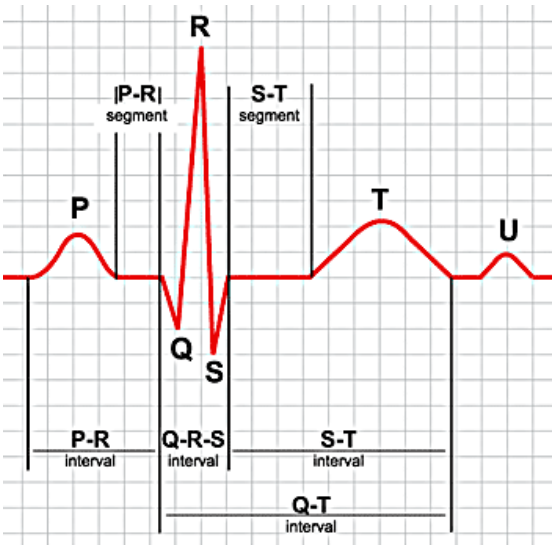

Figure 1 ECG waveform and names of waves and intervals

Information obtained from ECG can be divided into two categories: information related to timing of events such as HR, rhythm disturbance, and various intervals, and information related to the morphology of the waveforms.

Single-lead ECG can in most of cases, if a lead with adequate amplitude of signals can be selected, is enough to monitor the information related to the timing of the events. Monitoring ECG, where only two or three electrodes are attached, can only provide a limited numbers of leads. However, for the evaluation of the information related to the morphology of the waveforms, as these waveforms are time-related changes in the three-dimensional vector, single-lead ECG or ECG with limited number of leads are insufficient for clinical use and hence the use of a standard 12-lead ECG has been advocated.

1.2. Lead systems in ECG monitoring

The 12-lead system is a standard lead system used in ECG's. The standard 12-lead ECG was designed to show the frontal components of the three-dimensional electric vector in six limb leads, and the horizontal components in six precordial leads. (Figure 2)

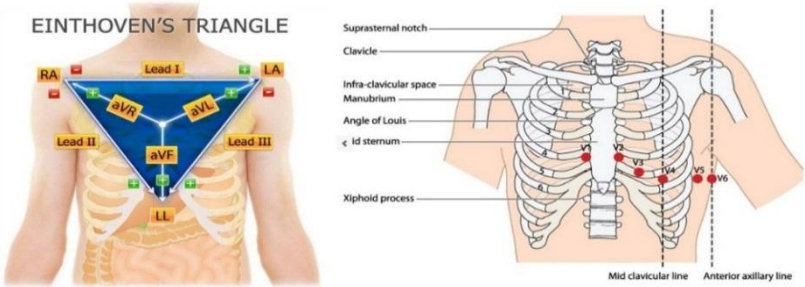

Figure 2. Limb and precordial leads in standard 12-lead ECG

In the frontal plane leads (I, II ,III, aVR, aVL, aVF), the vector component of the frontal plane in I II and III are mathematically described as II = I + III. The augmented leads, aVR, aVL and aVF, can also be derived from leads I, II and III. Therefore, with any two of leads I, II, and III, we can reconstruct six frontal plane ECGs.

As precordial lead attachment sites are located anteriorly for the convenience of patient and covering the anterior half of the body, the electric vector direction in a certain position in the horizontal plane may lead to underestimation of the magnitude of vector in the currently used system.

The horizontal plane in the standard 12-lead ECG system is located at the level of the heart. Picking up this plane for the horizontal leads is based on the assumption that cardiac electric vector originates at the center of the heart. If we obtain signal from the plane far apart from the heart level, horizontal component of the electric vector can be underestimated.

1.3. Clinical needs for the number and location of electrodes

Attaching 10 electrodes for the standards 12-lead ECG has been a standard procedure for clinical use. However, these large number of electrodes are not suitable for monitoring purposes. Therefore, obtaining one to 3-4 leads from two to four electrodes has been used clinically. Furthermore, to be used in the ambulatory setting, electrode locations should be close enough to be packed into a patch. In this study, we

designed 3-lead patch-type device with four electrodes inside the device.

1.4. Theoretical aspect

For the synthesized ECG, different equations are used for each lead to make a 12-lead ECG. In personalized transformation, these equations are decided for the individual use, and different set of equations are needed for different patients. Universal transformation involves using a single set of equations in every patient. Personal transformation has a critical limitation in the clinical value, as the individualized set of equations should be installed for each patient. Theoretically, obtaining synthesized ECG from personal transformation will likely to be closer to using standard 12-lead ECG. However, personal transformation also has intrinsic limitations. As the direction of electric vectors of each component of the ECG signal, e.g. the P wave, QRS complex, direction of ST segment if present, the T wave differ, and therefore may need separate transformation equations for each component of the waveform to reconstruct identical ECG Clinical usefulness does not lie in identicalness. If pertinent information with regard to the magnitude and direction of the electric vector can be delivered to the physician, clinical usefulness can still be maintained. ,

2. Method

2.1 Mobile ECG system design

We established a system composed of a patch-type device, the analysis program MATLAB (MathWorks, MA, USA) and a commercial standard ECG device (MAC5500, GE, USA). ECG data from the device was transferred wirelessly to PC using a Bluetooth module. At the time of obtaining ECG data using the standard ECG device for 10s, the data from the 3-lead patch-type device was recorded simultaneously. Signals from the commercial ECG device and our patch system were digitally stored. Validation of the analog conversion of the digitally stored signal from the commercial ECG was performed by confirming the identicalness of the printed out 12-lead ECG.

2.2. Hardware

A patch-type device was designed to measure 3-lead ECG from the left-upper chest (Figure 3). The distances between electrodes and electrode locations were decided according to a previous study[4].

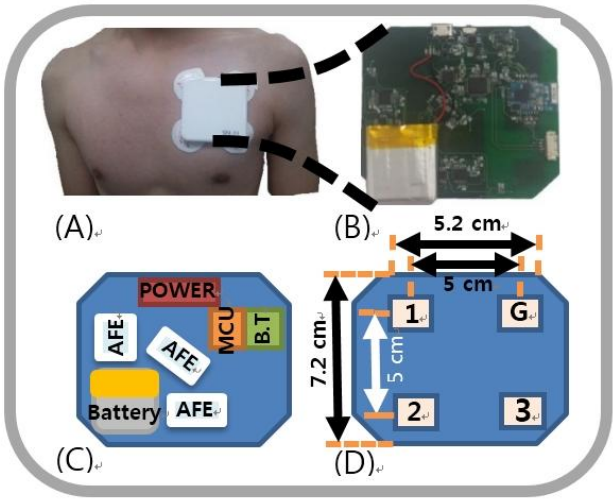

Figure 3. (A) Picture of the device attached on patient. (B) Cutomized circuit (C) Components of the front side (D) Components of the back

side

A previous study reported that reconstructed ECG from 3-leads obtained from the left-upper chest resulted in the highest correlation with standard 12-lead signals. The ECG signal was band-pass filtered between 0.05-150Hz according to American Heart Association's (AHA) recommendation [5] and amplified by a factor of 1000. Signals were digitized using a 16-bit sigma-delta analog-to-digital converter (STM32F373, STMicroelectronics, Switzerland) at 250Hz and were transmitted by a Bluetooth module(Bot-CLE110, Chipsen, South Korea) to a PC for data processing(Figure 4,5). The circuit was implemented on a customized printed circuit board. The developed device measured 80 mm in length and width, 13 mm in thickness and 90g in weight. The resolution of the device was 16 bits with a sampling rate of 250 Hz

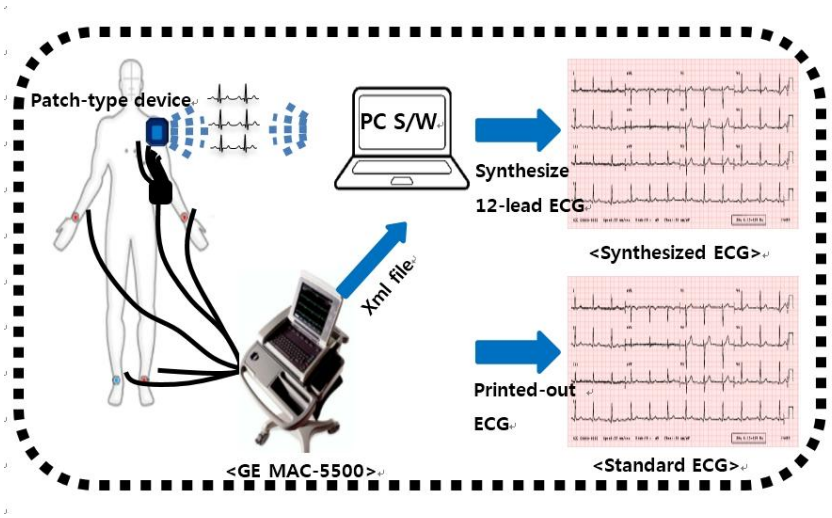

Figure 4. System for clinical validation of reconstructed ECG from a patch-type device

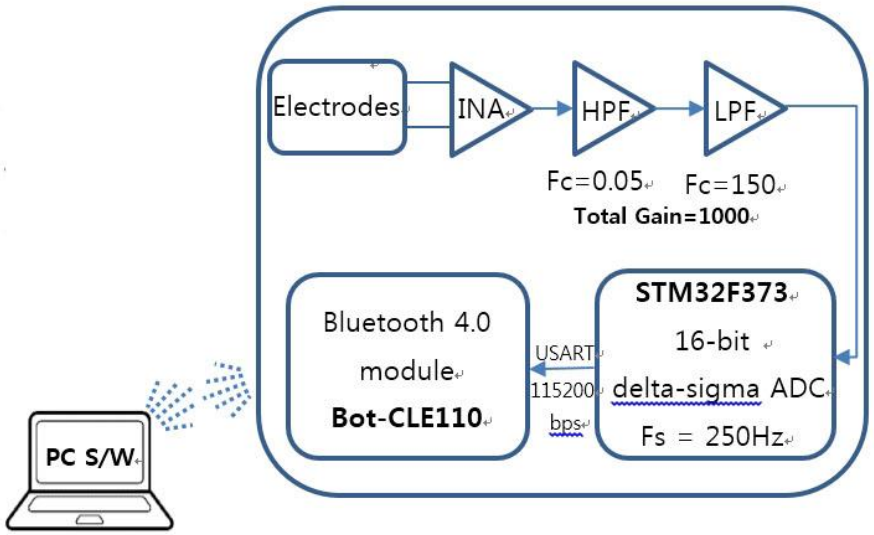

Figure 5. Block Diagram of signal processing and data acquisition stage of the device

2.3 Software

2.3.1 Data acquisition system

The data acquisition program was developed using LabView (National Instrument, Austin, TX) (Figure 6). It can receive a 3-lead ECG signal continuously and save it as a text file. On the operator setting the comport number and pressing the start button, waveforms transferred from the device are plotted on the graph. After checking the signal quality, the operator presses the save button before recording the standard 12-lead ECG. After designating the file name and location, data are aligned vertically in the file

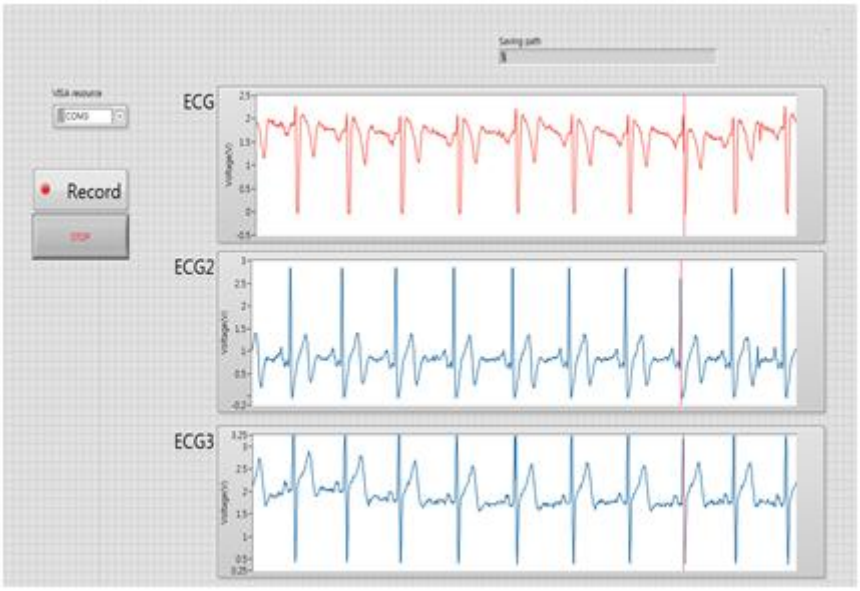

Figure 6. Screenshot of the acquisition program's user interface

2.3.2 Data analysis program

To compare the signals' equality, we extracted diagnostic parameters such as the P amplitude, PR interval, QRS voltage and duration and QT duration. We developed an analysis program using MATLAB (MathWorks, MA, USA) that can align the ECG signals and segment the P, Q, R, S, and T waves. First, we detected the R peak using the Pan-Tompkins algorithm[6]. This algorithm uses the characteristics of the QRS complex, which contains 8-16 Hz components compared to other complexes and having rapidly changing slopes. We can detect the R peak easily by a bandpass filter and derivatives. After obtaining R peak in this way, other peaks such as P, Q, S, and T are detected using ECGPUWAVE [7] which is Physionet's open source algorithm. ECGPUWAVE algorithm, made by using the CSE database, is a

grouping morphology that makes a decision tree based on the characteristics of the group. After getting the onsets, offsets and peaks of P, Q, R, S, and T, we calculated the above mentioned cardiac parameters. Figure 7 is a screenshot of the developed user interface for the ECG analysis program. User-loaded ECG raw data appears in the upper graph, and the leads of the ECG can be chosen at the popup menu on the right side. When the operator presses the segmentation button after choosing the leads, P, Q, R, S, and T onsets, offsets, and peaks were detected as mentioned above. Diagnostic results also appear at the bottom of GUI. As diagnostic results, only pathologic ECG findings pertinent to our experiment were included: wide QRS, ST depression, ST elevation, and pathologic Q wave.

Diagnostic result was decided based on the following criteria.

Wide QRS: QRS duration ≥ 120 ms: ST elevation: elevation of ST segment ≥ 1mm 0.08 ms after J point: ST depression: depression of ST segment ≥ 1mm 0.08 ms after J point: Pathologic Q wave; amplitude ≥25% of R wave, ≥0.04 ms in duration

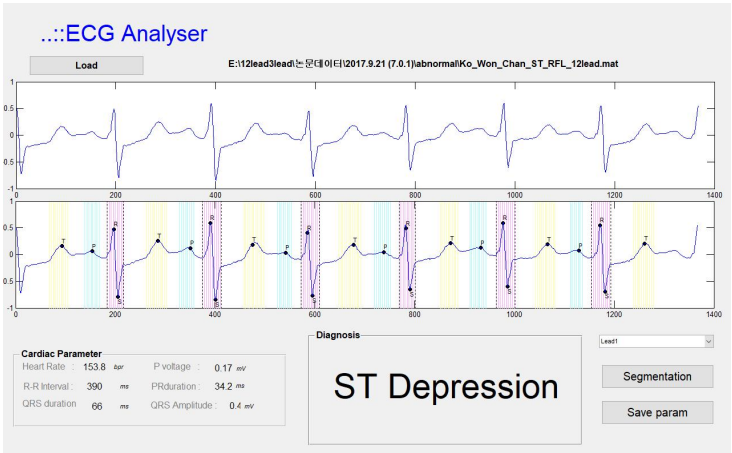

Figure 7. User interface of the analysis program

2.3.2.1 Linear Regression

For reconstructing the 12-lead ECG from the 3-lead ECG, we used the linear regression method which is widely used in the previous reconstructed ECG studies[8-10].

$$Y = \alpha * X + \beta$$

Y contains target standards of the 12-lead ECG which we want to reconstruct. α is a transformation matrix needed for reconstructing the synthesized ECG. X is a combination of the reduced number of ECG data. β is a matrix that contains vectors of error. We used the least squares method for obtaining the transformation matrix α with training data. Once α was obtained, we synthesized the 12-lead ECG with test data. There are two methods used in the reconstruction of the 12-lead ECG using linear regression. The first method is to obtain the transformation matrix X individually. Since subjects have their own electric vectors, assuming the electrical activity of the heart as a single fixed location dipole. However, applying this personal transformation in a commercial device system is cumbersome as patients should calibrate their device with standard 12-lead ECG device individually. In the second method, universal transformation using a common transformation matrix is established by using data from 15 normal subjects. Therefore, universal transformation may not be well fitted individually compared to personalized

transformation. However, this method can be readily applied for a commercial 3-lead device system.

2.4 Enrollment of subjects

2.4.1 Informed consent

All subjects provided informed consents, and the study was approved by the institutional review board of Seoul National University Hospital (IRB No. 1707-094-870)

2.4.2 Normal subjects

For the normal ECG findings, 10 normal subjects were recruited. All these subjects were taking ECG examination as a preoperative routine. All subjects were negative for cardiac symptoms and showed normal echocardiographic findings.

2.4.3 Subjects with pathologic ECG findings

2.4.3.1 ECG showing ST depression

Because of the rarity of ST depression in resting ECG, the device was attached on the chest wall before exercise in 29 patients undergoing the treadmill exercise test after the informed consent. If the patient showed ST depression, the 12 lead-ECG signal and signal from the patch system were simultaneously obtained immediately after exercise in the sitting position to avoid motion artifact. Five patients with ST depression were enrolled.

2.4.3.2. Pathologic findings other than ST depression.

For the pathologic findings other than ST depression, 33 admitted patients who were taking ECG for clinical purposes and agreed to participate in this study were enrolled. Patients with irregular rhythms such as atrial fibrillation, or low voltage or poor signal quality due to labored respiration or involuntary muscle movement were excluded. Patients with the following ECG findings were asked to participate in this study: LVH, bundle branch block, ST depression for elevation either anterior(lead V1, V2 orV3) or inferior leads (lead II, III or aVF), pathologic Q wave (q wave > 25% of QRS complex or ≥ 0.04 ms in duration) either anterior or inferior leads and T wave inversions in the lateral precordial leads.

2.5 Statistics

All measurements were expressed as mean±SD. For comparison of normal parameters measured by the standard 12-lead ECG and synthesized ECG by personal and universal transformations, Kruskal-Wallis test was used. A p-value less than 0.05 was considered statistically significant. To evaluate the usefulness of the synthesized ECGs, sensitivity and specificity were used.

3. Results.

3.1 Feasibility of personalized and universal transformations

Correlation coefficients and root-mean-square errors (RMSE)

between standard 12-lead and synthesized ECGs are as follows: (Figure 8, Table 1)

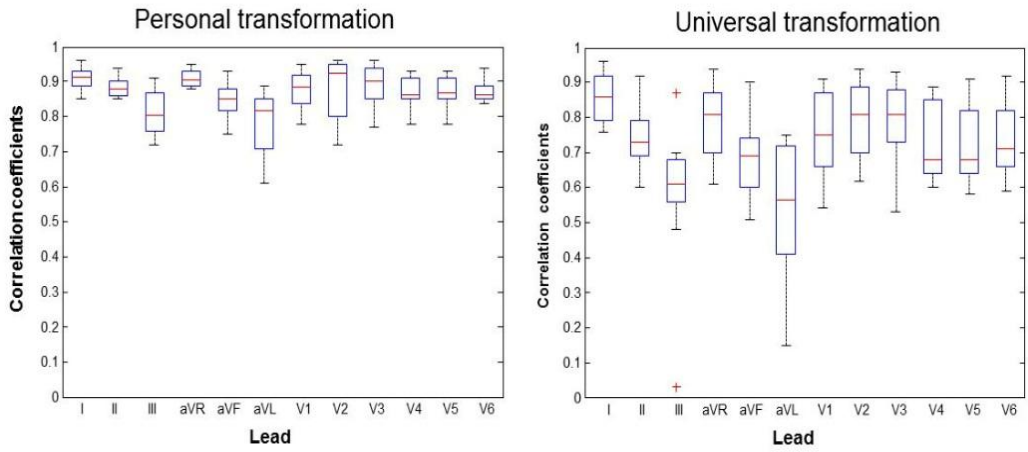

Figure 8. Correlation coefficients between standard 12-lead ECG and synthesized ECG's

Table 1. Correlation coefficients and RMSE between standard 12-lead and synthesized ECG

		I	II	III	aVR	aVF	aVL	V1	V2	V3	V4	V5	V6
CC	Personalized	0.91	0.87	0.81	0.90	0.85	0.78	0.85	0.87	0.89	0.87	0.87	0.87
	Universal	0.86	0.74	0.58	0.79	0.68	0.53	0.75	0.79	0.78	0.73	0.73	0.73
RMSD	Personalized	12.51	55.55	55.00	30.49	53.92	26.91	24.08	29.47	32.92	42.62	46.99	43.36

3.2 ECG parameters in normal subjects

Both personal and universal transformation did not show significant differences in the xis, P wave amplitude, PR interval, QRS duration, QT duration and T wave amplitudes in lateral precordial leads from the standard 12-lead ECG. A comparison of the parameters is presented in Table 2

Table 2 . Comparision of parameters measured in normal subjects by three differnent systems.

EKG Parameters	Standard EKG	Synthesized EKG: Personal	Synthesized EKG: Universal	P-value
Axis (degree)	53.0±12.5	56.8±12.4	57.0±14.5	n.s.
P wave: Amplitude in lead II (mV)	1.48±0.93	0.9±0.86	0.69±0.39	n.s.
Visible leads No. (No.)	10.1±3.1	8.2±3.4	7.4±3.8	n.s.
PR interval (msec)	0.21±0.21	0.15±0.03	0.16±0.02	n.s.
QRS: Duration (msec)	0.09±0.01	0.09±0.01	0.1±0.011	n.s.
Total voltage	157.4±27.9*	120.3±30.6	96.1±30.6*	0.004
QT duration (msec)	0.44±0.19	0.38±0.04	0.37±0.04	n.s.
T wave amplitude in V4 (msec)	2.2±1.4	2.3±1.5	2.2±1.3	n.s.
V5 (msec)	2.3±1.4	2.3±1.0	2.0±1.2	n.s.
V6 (msec)	1.7±1.0	2.0±0.7	1.5±0.9	n.s.

* : P<0.04

However, the reconstructed ECG showed the tendency of smaller voltage in QRS and the difference was statistically significant between the standard ECG and the synthesized ECG obtained by universal transformation.
This tendency was also noted in the P wave amplitude, although it was not statistically significant. Therefore, the number of leads

with discernible P waves showed a similar trend.
These findings, considering the relatively accurate estimation of axis and durations, might indicate that the reconstructed ECG can adequately reflect vector directions but has a limitation in reflecting accurate vector magnitudes.

3.3 Clinical validity in pathologic ECG

The diagnostic sensitivity and specificity of the reconstructed ECG in predicting various pathologic ECG findings are listed in table 3.

Table 3. Sensitivity and specificity of reconstructed ECG in detecting various pathologic conditions in ECG obtained in 38 patients

Parameters	Synthesized EKG: Personal		Synthesized EKG: Universal	
	Sensitivity (%)	Specificity (%)	Sensitivity (%)	Specificity (%)
LVH (n=14)	93	100	57	100
Wide QRS (QRS > 120msec) (n= 6)	100	77	100	79
Pathologic Q ant and inf combined (n=13)	82	100	82	100
Pathologic Q in ant (n= 8)	88	100	88	100
ST elevation ant and inf combined (n=7)	29	97	14	97
ST depression in inf and lat combined (n=10)	30	97	40	93
T wave inversion in V4-6 (n=9)	100	93	100	93

3.3.1 LVH

Although specific, as with the tendency of the low voltage in the QRS complex seen in normal subjects, the sensitivity of detecting

LVH was not good especially in universal transformation. (Figure 10)

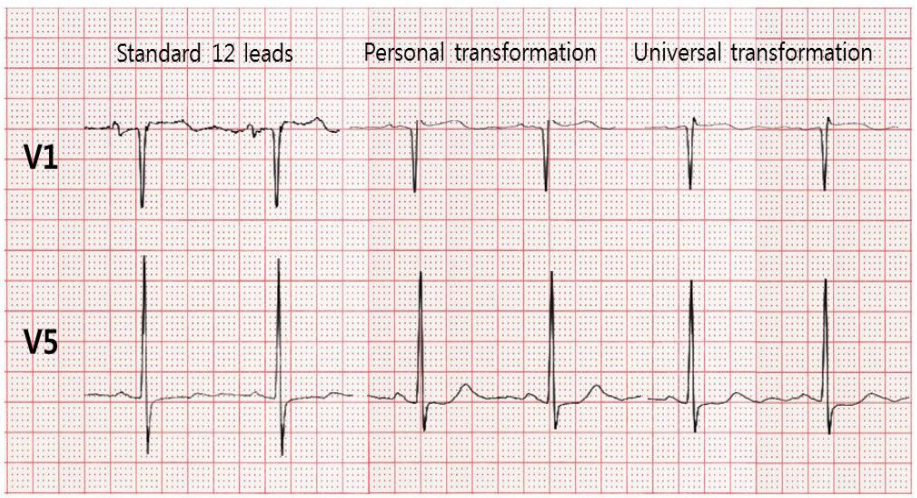

Figure 9 . Reconstructed ECG showed the tendency of slightly reduced voltages. This phenomenon resuled in unfulfilling the diagnostic criteria of LVH (S1 + R5 or R6 greater than 35mV), thereby leading to false negative results. LVH: left ventricular hypertrophy.

3.3.2 ST changes

3.3.2.1 False negative

In contrast to predicting the presence of Q wave or T wave inversion, limited sensitivities of detecting ST segment changes in our study indicate that reconstructed ECGs are not clinically applicable for the detection of ST changes, both in the cased of ST depression (Figure 9) and ST elevation (Figure 10).

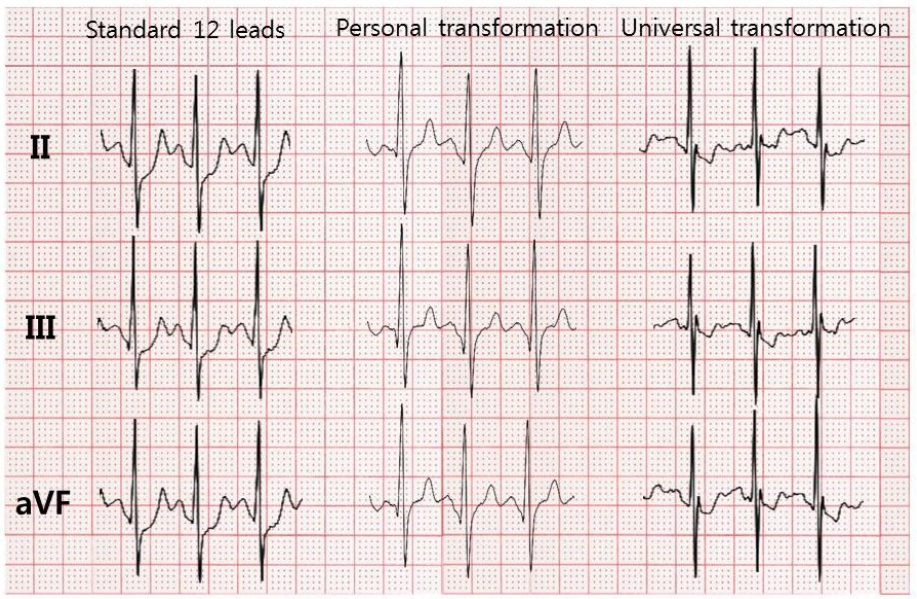

Figure 10. False negative finding in reconstructed ECGs in ST depression.

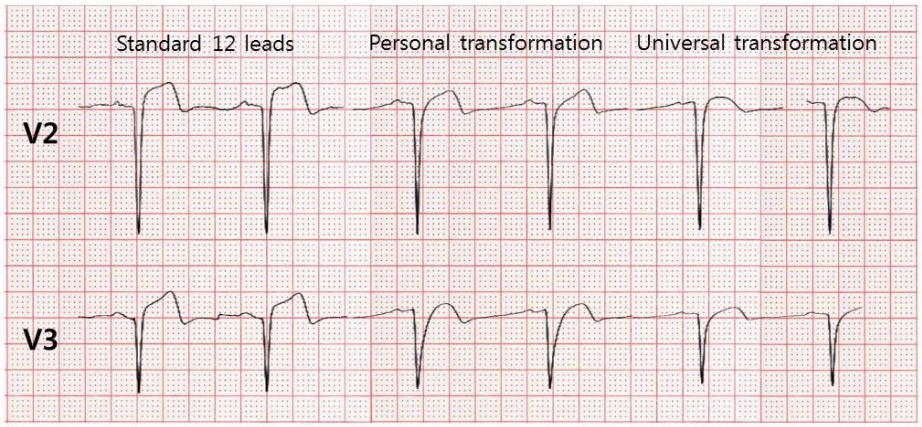

Figure 11. False negative finding in reconstructed ECG' s in ST elevation.

3.3.2.2 False positive

In one patient, false positive ST elevation in anterior leads was seen both in personal and universal transformations. (Figure 12) Two other patients showed false positive ST depressions, one patient in anterior leads in universal transformation only (Figure 13), and the other patient in inferior leads in both personal and universal transformations

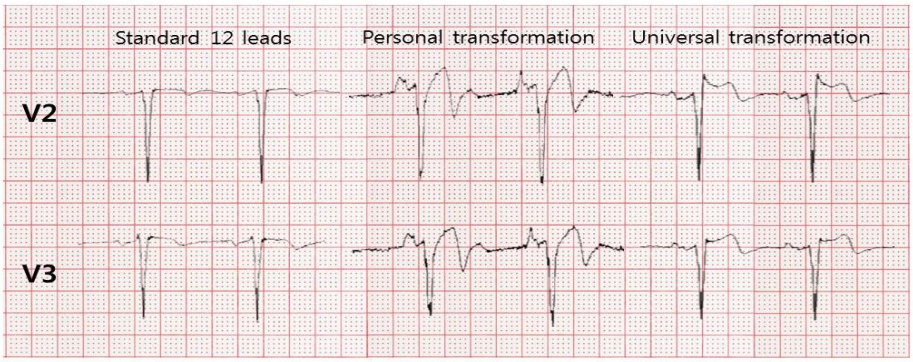

Figure 12. False positive ST elevation in reconstructed ECGs

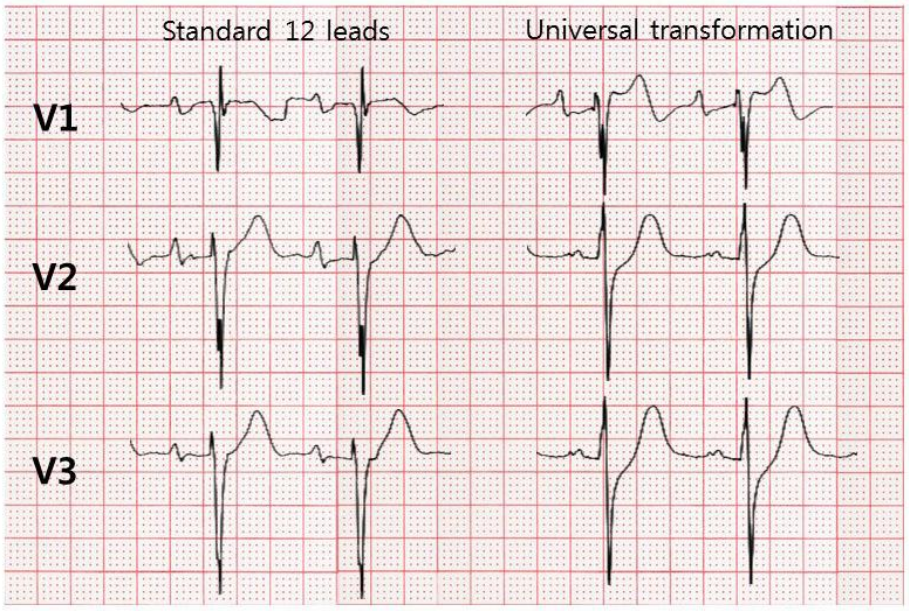

Figure 13. False positive ST depression in reconstructed ECGs by universal transformation

3.3.3 Wide QRS

The reconstructed ECG can sensitively detect wide QRS (QRS duration ≥ 120ms). However, several patients with narrow QRS showed wide QRS, resulting in a specificity of 77% and 79% in personal and universal transformation, respectively.

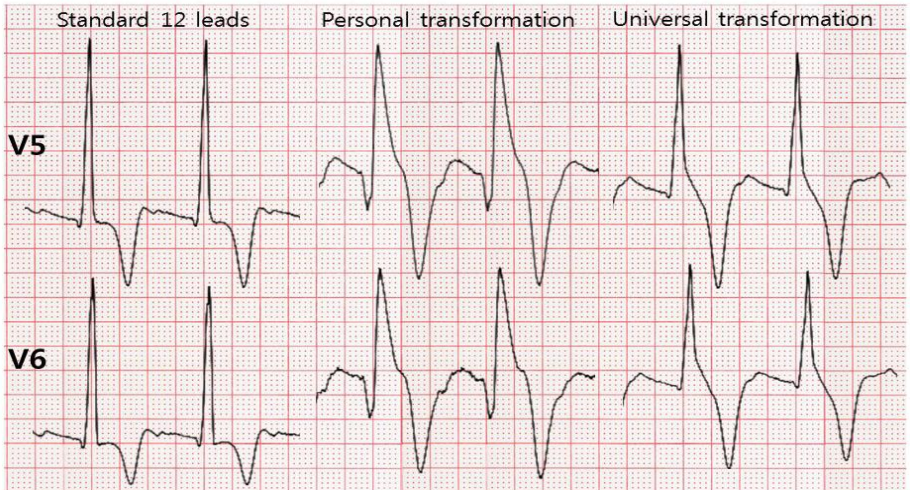

Figure 14. Markedly increased QRS durations in the reconstructed ECGs

The QRS configuration that may result in markedly deformed QRS (Figure 14) in reconstructed ECGs cannot be deduced solely from our study. However, three patients among seven with false positive wide QRS showed a marked difference in voltages between limb leads and precordial leads (Figure 15)

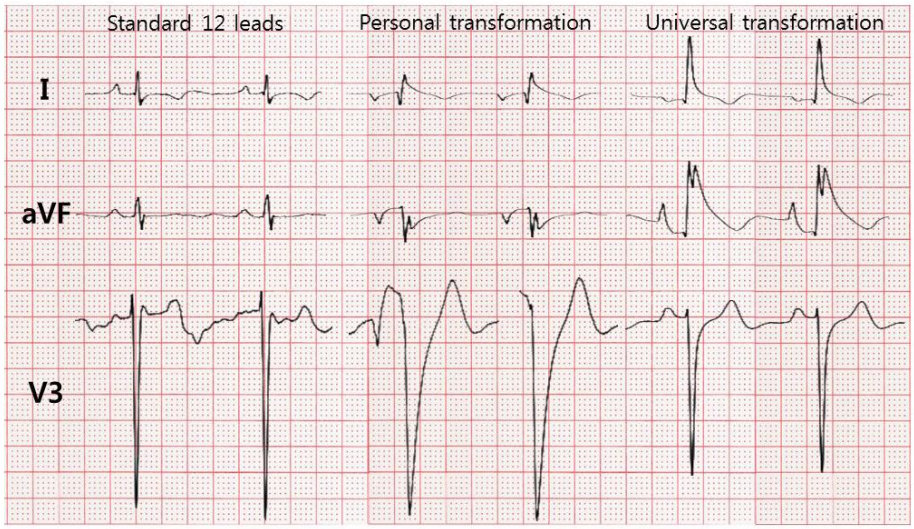

Figure 15. In patients with large difference in voltages of QRS complexes between limb leads and horizontal leads, resulting in false positive wide QRS.

in the horizontal plane, reconstructed ECGs might likely show deformed QRS complex as our leads system predominantly reflect frontal plane vectors and has intrinsic limitation in

detecting horizontal component of QRS vector

4. Discussion

Synthesized ECG obtained with a reduced number of leads has been studied because of the clinical need of continuous patient monitoring in intensive care, for telemetry, or usage in other diagnostic test machines. Those studied were designed to reduce the number of electrodes from the standard lead positions [11-13]. Three or four lead positions selected in those studies were leads I, II, V3 and V5 or V6. For achieving the best performance, those studies included precordial leads that can represent vector component in the horizontal plane (V3, V5 or V6). In one of those studies [13], when only one precordial electrode location was used for reconstruction, the correlation coefficient drop to 0.854 (0.642-0.912). Our patch-type device has an intrinsic limitation in capturing the horizontally directed components of cardiac vectors. When our patch system is attached on the patient, only a small difference in anterior-posterior locations exists among electrodes. This small difference in the anterior-posterior locations should replace the role of precordial leads in the standard 12-lead ECG.

In recent years, with the achievements in engineering, medical devices are becoming miniaturized and wireless and suitable for ambulatory use. In line with such advancement, not only should the numbers of electrodes be reduced but lead locations should also be close enough to be packed into a patch system [14, 15].

Although a number of patch systems are commercially available, majority of the commercially available patch-type electrodes are single-lead systems. Therefore, reconstruction of 12-lead ECG cannot be pursued. Theoretically, three electrodes for two pairs of leads are the minimum number of electrodes needed, with one lead representing the frontal plane and the other representing the horizontal plane, for the reconstruction of 12-lead ECG. We incorporated this minimum number of electrodes in our patch-type system.

Eliminating motion artifacts is a key problem encountered during ECG monitoring. Many algorithm have been proposed [16-21] to eliminate artifacts after signal acquisition, and various techniques have been proposed for use at the time of signal

acquisition. In our patch-type system, only a swinging of the baseline associated with respiration was noted, and this can be easily eliminated by incorporating a low-pass filter. However, we tested our patch-type device only in the resting state. Problems associated with motion artifacts when our system is applied in an ambulatory setting should be evaluated and solved in future studies.

With signal obtained from our patch-type system, synthesized 12-lead ECG showed correlation coefficients of 0.86 (0.77-0.92) and 0.72 (0.65-0.86) with the standard 12-lead ECG in personal and universal transformations, respectively. In a previous study [13], when the three leads I, II, and V2 were used for reconstruction, correlation coefficients were 0.98 (0.96-0.99) and 0.91(0.86-0.95) in personal and universal transformation. Inferior correlation coefficients in our study are

quite expected owing to the locations of electrode placement used in our system, and this is an unavoidable drawback to be used in the ambulatory system.

Admitting the inferiority in obtaining a waveform identical to the standard 12-lead ECG, if the vital information can be obtained even in slightly different ECG waveforms, clinical usefulness can still be maintained.

In the measurement of normal parameters, no significant differences existed among the standard 12-lead ECG and the synthesized ECG using personal and universal transformations, excerpt for the total QRS voltages. Therefore, even though the synthesized ECGs tend to show small QRS complexes, these ECG's are well suited for the ambulatory monitoring of cardiac rhythm. For the limited use of monitoring rhythm disturbances, even a single lead may suffice. However, the basic requirement of ECG monitoring is that, the amplitude of the monitored ECG should be adequate, that is, it should not be too small. Among the 120 ECG signals from 12 leads in ten normal subjects, 38% of the signals were less than 10 mV in amplitude, and hence not desirable for monitoring, especially in an ambulatory setting. Even in such area as monitoring rhythm disturbance where single lead system is suffice, relocating the electrode positions to acquire ECG signals with better amplitude can be avoided by using our device.

As regards diagnostic usefulness, both personalized and universal transformations can well predict pathologic findings associated with the change in the direction of the cardiac electric vectors as presence of pathologic Q wave and T wave inversions. However, in the detection of the magnitude of

change in cardiac electric vectors, such as ST segment elevation or depression [22], synthesized ECG's are relatively insensitive. To be applied in the early detection of ischemia, our system is not optimal. As our patch-type device can incorporate other sensors such as accelerometer, combining the information from more sensors might overcome this limitation. In addition to this insensitivity, several cases of false positive results were obtained. The most conspicuous false positive result was the false positive wide QRS finding. As this wide QRS morphology can possibly be mistaken as serious ventricular arrhythmia, initial check-up for the narrow QRS complex is required. We do not precisely explain the cause of this phenomenon, as this phenomenon is more likely to be seen in patients with a large discrepancy in the amplitudes of signal from limb and precordial leads.

5. Conclusion

In conclusion, 12-lead ECG was reconstructed from 3 lead patch-type device and, validated in the measurements of normal parameters and diagnosing pathologic findings. Our system can give accurate informations about the change in axis, presence of Q wave or change in T wave direction that a single-lead ECG cannot provide, therefore, helpful in the detecting the pathologic findings. However, our system showed limited sensitivity in detecting ST changes and may show false positive wide QRS complexes.

6. References

[1] S. S. Barold, "Willem Einthoven and the birth of clinical electrocardiography a hundred years ago," *Card Electrophysiol Rev,* vol. 7, no. 1, pp. 99-104, Jan 2003.

[2] P. Kligfield *et al.*, "Recommendations for the standardization and interpretation of the electrocardiogram: part I: the electrocardiogram and its technology a scientific statement from the American Heart Association Electrocardiography and Arrhythmias Committee, Council on Clinical Cardiology; the American College of Cardiology Foundation; and the Heart Rhythm Society endorsed by the International Society for Computerized Electrocardiology," *J Am Coll Cardiol,* vol. 49, no. 10, pp. 1109-27, Mar 13 2007.

[3] J. W. Mason *et al.*, "Recommendations for the standardization and interpretation of the electrocardiogram: part II: electrocardiography diagnostic statement list a scientific statement from the American Heart Association Electrocardiography and Arrhythmias Committee, Council on Clinical Cardiology; the American College of Cardiology Foundation; and the Heart Rhythm Society Endorsed by the International Society for Computerized Electrocardiology," *J Am Coll Cardiol,* vol. 49, no. 10, pp. 1128-35, Mar 13 2007.

[4] H. J. Lee, D. S. Lee, H. B. Kwon, D. Y. Kim, and K. S. Park, "Reconstruction of 12-lead ECG Using a Single-patch Device," *Methods Inf Med,* vol. 56, no. 4, pp. 319-

327, Aug 11 2017.

[5] J. J. Bailey *et al.*, "Recommendations for standardization and specifications in automated electrocardiography: bandwidth and digital signal processing. A report for health professionals by an ad hoc writing group of the Committee on Electrocardiography and Cardiac Electrophysiology of the Council on Clinical Cardiology, American Heart Association," *Circulation,* vol. 81, no. 2, pp. 730-9, Feb 1990.

[6] J. Pan and W. J. Tompkins, "A real-time QRS detection algorithm," *IEEE Trans Biomed Eng,* vol. 32, no. 3, pp. 230-6, Mar 1985.

[7] P. Laguna, R. Jane, and P. Caminal, "Automatic detection of wave boundaries in multilead ECG signals: validation with the CSE database," *Comput Biomed Res,* vol. 27, no. 1, pp. 45-60, Feb 1994.

[8] R. Trobec and I. Tomasic, "Synthesis of the 12-lead electrocardiogram from differential leads," *IEEE Trans Inf Technol Biomed,* vol. 15, no. 4, pp. 615-21, Jul 2011.

[9] I. Tomasic, S. Frljak, and R. Trobec, "Estimating the Universal Positions of Wireless Body Electrodes for Measuring Cardiac Electrical Activity," *IEEE Trans Biomed Eng,* vol. 60, no. 12, pp. 3368-74, Dec 2013.

[10] I. Tomasic and R. Trobec, "Electrocardiographic systems with reduced numbers of leads-synthesis of the 12-lead ECG," *IEEE Rev Biomed Eng,* vol. 7, pp. 126-42, 2014.

[11] L. D. Cady, Jr., "Computed relationship of standard electrocardiographic leads," *Med Res Eng,* vol. 8, no. 3, pp. 37-42, May-Jun 1969.

[12] J. A. Scherer, J. M. Jenkins, and J. M. Nicklas, "Synthesis of the 12-lead electrocardiogram from a 3-lead subset using patient-specific transformation vectors. An algorithmic approach to computerized signal synthesis," *J Electrocardiol,* vol. 22 Suppl, p. 128, 1989.

[13] S. P. Nelwan, J. A. Kors, S. H. Meij, J. H. van Bemmel, and M. L. Simoons, "Reconstruction of the 12-lead electrocardiogram from reduced lead sets," *J Electrocardiol,* vol. 37, no. 1, pp. 11-8, Jan 2004.

[14] S. S. Lobodzinski, "ECG patch monitors for assessment of cardiac rhythm abnormalities," *Prog Cardiovasc Dis,* vol. 56, no. 2, pp. 224-9, Sep-Oct 2013.

[15] T. Torfs *et al.*, "Clinical validation of a low-power and wearable ECG patch for long term full-disclosure monitoring," *J Electrocardiol,* vol. 47, no. 6, pp. 881-9, Nov-Dec 2014.

[16] Y. Wu, R. M. Rangayyan, and S. C. Ng, "Cancellation of artifacts in ECG signals using a normalized adaptive neural filter," *Conf Proc IEEE Eng Med Biol Soc,* vol. 2007, pp. 2552-5, 2007.

[17] S.-H. Liu, *Journal of Medical and Biological Engineering,* vol. 31, no. 1, p. 67, 2011.

[18] S. Kim, H. Kim, N. Van Helleputte, C. Van Hoof, and R. F. Yazicioglu, "Real time digitally assisted analog motion artifact reduction in ambulatory ECG monitoring system," *Conf Proc IEEE Eng Med Biol Soc,* vol. 2012, pp. 2096-9, 2012.

[19] J. Lee, D. D. McManus, S. Merchant, and K. H. Chon, "Automatic motion and noise artifact detection in Holter

ECG data using empirical mode decomposition and statistical approaches," *IEEE Trans Biomed Eng,* vol. 59, no. 6, pp. 1499-506, Jun 2012.

[20] Y. Tu *et al.*, "A novel method for automatic identification of motion artifact beats in ECG recordings," *Ann Biomed Eng,* vol. 40, no. 9, pp. 1917-28, Sep 2012.

[21] S. R. Subramaniam, B. W. Ling, and A. Georgakis, "Motion artifact suppression in the ECG signal by successive modifications in frequency and time," *Conf Proc IEEE Eng Med Biol Soc,* vol. 2013, pp. 425-8, 2013.

[22] R. E. Klabunde, "Cardiac electrophysiology: normal and ischemic ionic currents and the ECG," *Adv Physiol Educ,* vol. 41, no. 1, pp. 29-37, Mar 01 2017.

국문초록

패치형 3-리드 심전도 장치를 통해 재구축한 12-유도 심전도의 임상적 유용성에 대한 연구

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12 유도 심전도는 심장학분야에서 필수불가결한 진단적도구이다. 12 유도 심전도가 필요한 이유는 심장 이상의 종류와 발생 위치 등 다양한 다른 정보를 얻을 수 있기 때문이다. 한, 두 리드의 심전도로부터는 12 유도 심전도가 제공할 수 있는 정보 중 제한된 정보만을 얻을 수 있다. 그러나 12 유도 심전도를 얻기 위하여서는 10 개의 전극을 부착하여야 하며 이를 위해 넓은 부위의 흉부노출을 필요로 한다. 따라서 심전도 검사는 병원 내 검사에 제한되어 왔으나 최근 모바일 헬스케어 등 일상생활 중의 응용에 대한 필요성이 제시되고 있다. 이러한 임상적 요구에 따라 본 연구에서는 패치형장치에 포함시킨 3 개의 리드로부터 12 유도심전도를 재구성하였고 이 재구성된 12 유도 심전도가 임상적으로 유용한가를 평가하기 위하여 표준 12 유도 심전도와의 유사성을 비교하고, 심장 질환 환자에 대한 진단능도 평가 하였다.

재구성된 12 유도 심전도는 개인형 변형공식방식과 15 명의 정상인으로부터 얻어진 공통 변형공식을 이용한 두 가지 방식으로 재구성하였다.

재구성 심전도 신호의 평가를 위해 정상인 10 명을 대상으로 정상 지표들을 측정하는데 있어서의 유용성을 검증하였다. 개인형 변형공식방식과 공통 변형공식방식으로 얻어진 지표들과 표준 12 유도 심전도로부터 얻어진 지표들 사이에 총 QRS voltage 이외에는 유의한 차이를 보이지 않았다. 총 QRS voltage 에 있어서는 공통 변형공식로 얻어진 총 QRS voltage 가 표준 12 유도 심전도로 얻어진 것 보다 유의하게 작았다($p < 0.04$)

병적소견 심전도를 보이는 38 명의 환자에서 표준 12 유도 심전도로 얻어진 진단을 기준으로 하여, 개인형 변형공식방식과 공통 변형공식방식으로 얻어진 심전도의 진단적 예민도와 특이도를 평가하였다. 병적소견으로는 LVH 14 건, wide QRS ($\geq$ 120 ms) 6 건, patholoigic Q 6 건, ST 상승 7 건, ST 하강 10 건 및 T 역위 9 건이 있었다. 개인형 변형공식방식과 공통 변형공식방식 두 방식 모두 전기벡터의 방향의 변화와 연관된 Q 파의 존재유무나 T 파의 역위를 평가하는데는 좋은 예민성과 특이성을 보였다. 그러나 적은 양의 전기벡터의 크기의 변화와 연관된 ST 절 상승이나 하강을 평가하는데는 제한적이어서 개인형 변형공식방식 및 공통 변형공식방식 각 방식의 예민도는 ST 절 상상에 있어 각각 19%, 14%였으며, ST 상승에 있어 각각 30%, 40%였다. 또한 wide QRS 를 평가하는데 예민도는 좋았으나 일부 환자에서는 narrow QRS 가 wide QRS 로 나타나는 경우들이 있어 특이도에 있어서 개인형 변형공식방식 및 공통 변형공식방식은 각각 77%, 79%였다.

결론적으로 패치형 3 리드시스템으로 12 유도 심전도를 재구성할 수 있었으며 정상지표들을 측정하는데 유용하였고 단일리드 심전도에 비하여 추가적인 정보를 제공할 수 있었다. 그러나 ST 절 변화를 감시하기에는 제한이 있을 것으로 보이며 일부 wide QRS 에 대한 위양성 소견도 나타나니 이에 대한 성능 개선을 통해 모바일 헬스케어 서비스 등에 활용될 수 있을 것으로 기대된다.

Keywords: 심전도 자동 분석, 패치형 심전계, 합성 12 유도 심전도, 병적 심전도