# Design and Evaluation of A Novel Wireless Three-pad ECG System for Generating Conventional 12-lead Signals *

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## ABSTRACT

Electrocardiography (ECG) is a widely accepted approach for monitoring of cardiac activity and clinical diagnosis of heart diseases. In order to make ECG systems portable, easy to setup, comfortable to patients and tolerant of artifacts, wireless single-pad ECG systems have been developed. To tackle the problems raised by wireless single-pad ECG systems, we propose an upgraded version, the wireless three-pad ECG system (W3ECG). W3ECG furthers the pad design idea of the single-pad approach. We add two more pads to the W3ECG to gain spatial variety of heart activity. Signals obtained from these three pads, plus their placement information, make it possible to synthesize conventional 12-lead ECG signals. We provide one example of pad placement and evaluate its performance by examining ECG data of four patients available from online database. Feasibility test of our selected pad placement positions show comparable results with respect to the EASI lead system. Experimental results also exhibit high correlations between synthesized and directly observed 12-lead signals (9 out of 12 cross-correlation coefficients higher than 0.75).

## Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous

## 1. INTRODUCTION

Electrocardiography (ECG) is a widely accepted approach for monitoring of cardiac activity and clinical diagnosis of heart diseases, particularly those caused by damages to the conductive tissues or levels of dissolved salts, and observed in the form of abnormal rhythms [18]. By sensing and amplifying body-surface potentials at electrodes, an ECG system gives potential differences across these electrodes.

*This work was supported in part by the Canadian Natural Sciences and Engineering Research Council under grant STPGP 365208-08.


*BodyNets* 2010 Corfu Island, Greece


There is no consensus on either the optimal quantity or placement positions of an ECG system's electrodes; they largely depend on a particular application [10]. While the two parameters are yet to be optimized, various ECG systems have been developed. They can be classified into four groups, namely conventional 12-lead ECG systems, electrocardiographic body surface mapping (BSM) systems, vectorcardiographic (VCG) systems, and wireless single-pad ECG systems. Each system can be seen as a particular configuration of the above two parameters.

Conventional 12-lead ECG systems require 10 electrodes on the patient's torso. These electrodes form 12 leads. Since cardiologist have been well-trained to accept 12-lead ECG information, a huge number of ECG systems are using such number of electrodes and placement configuration [6] to facilitate fast interpretation.

BSM systems originate in the 1960s. In such a system, a large number of electrodes (32 to 219) are placed on strips which are arranged around the circumference of the human torso. The potentials are simultaneously recorded and displayed on the map of a body surface model, and caregivers/researchers can have a full knowledge of bio-potential distributions on the torso [7][14][12]. However, the deployment complexity of BSM systems hinders their wide employment in the clinical environment.

A VCG system [16] registers electrical heart activity in three orthogonal leads. Based on a hypothesis that the electrical heart activity can be represented by a stationary dipole, the potentials recorded at the three leads are supposedly proportional to one rectangular component of the assumed heart dipole vector [11]. Under this assumption, signals recorded by a VCG system can be transformed to the 12-lead format. The advantage of this approach is the reduced number of electrodes. However, wires are still required to connect them. EASI lead system, an example of VCG system variant, has been approved by the US Food and Drug Administration for assessing normal, abnormal, and paced cardiac rhythms and for detecting myocardial ischemia or silent ischemia [4].

In order to make ECG systems portable, easy to setup, comfortable to patients and tolerant of artifacts, wireless single-pad ECG systems have been developed [17][13][5]. The so-called single-pad is a tiny printed circuit board (PCB) with three electrodes attached or embedded. It performs front-end ECG data acquisition, analog-to-digital conversion (ADC) and wireless transmission. However, as an ECG signal is dependent on placement position of electrodes, using such a single-pad approach, it is impossible to render caregivers conventional 12-lead ECG waveforms, which they have been trained to read [6].

To tackle the problem, we propose an upgraded version of it, the wireless three-pad ECG system (W3ECG). Inspired by application of linear transformations to ECG signals obtained in VCG systems, we add two more pads to the single-pad system to gain spatial variety of heart activity. Signals obtained from these three pads, plus their placement information, make it possible to synthesize conventional 12-lead ECG signals.

This paper is focused on W3ECG's system-level design, pad placements and evaluations. Pad design, software implementation, and experimental studies of W3ECG are detailed in an accompanying short paper [3]. The rest of this paper is organized as follows. Section 2 walks the readers through the derivation of the transformation equations used to synthesize 12-lead waveforms. Section 3 describes the system topology, synchronization scheme, and pad placement strategy. Section 4 presents feasibility tests and practical evaluation results. Section 5 concludes the paper and discusses future work.

# 2. DERIVATION OF TRANSFORMATION EQUATIONS

We first review the heart-vector projection theory [8]. Then by analyzing the clinical data sets available from Dalhousie University, we derive equations for linear transformation from W3ECG signals (obtained from the three W3ECG pads) to the 12-lead format.

## 2.1 Heart-vector Projection Theory

It is widely accepted that the electrical heart activity can be modelled as a stationary dipole [15][16]. Under this assumption, the heart dipole moment is a function of time and represented by a vector in the three-dimensional space as

$$\overline{p} = p_x\overline{x} + p_y\overline{y} + p_z\overline{z} \tag{1}$$

where $x$, $y$ and $z$ are standard unit vectors of a rectangular coordinate system. $x$ and $y$ axes span the frontal plane, $x$ and $z$ axes span the transverse plane, and $y$ and $z$ axes span the sagittal plane. In (1), $p_x$, $p_y$ and $p_z$ are projections of the heart dipole moment $\overline{p}$ on three axes, representing the scalar components of $\overline{p}$. This is illustrated in Figure 1. Elements of $\overline{p}$ are in units of $mA \times cm$. The potential $V_i$

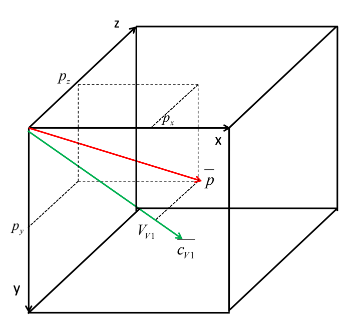


**Figure 1: Illustration of the heart vector and its projection on a lead vector.**

(subscript $i$ is for distinguishing torso locations) $\overline{p}$ produces on the torso is the multiplication of $\overline{p}$ and a resistive component $\overline{c_i}$, which is a function of shape, size, and characteristics of the medium, the position of the dipole as well as where the potential is measured (position of electrode on torso). Assuming homogeneity and thus linearity of the medium, the electric potential appearing at any torso location is represented as the projection of $\overline{p}$ on $\overline{c_i}$ as

$$V_i = \overline{c_i} \cdot \overline{p} \tag{2}$$

where $\overline{c_i}$ is called the lead vector with units of $\Omega/cm$. For example, as shown in Figure 1, the lead V1 in the 12-lead system can be expressed as

$$V_{V1} = \overline{c_{V1}} \cdot \overline{p} \tag{3}$$

## 2.2 Analyzing Clinical Data Sets

### 2.2.1 Objective

Our goal is to design a wireless ECG system which provides conventional 12-lead ECG information without wires between electrodes. To eliminate the wires, one way, is to attach 4 electrodes to one pad, and make the pad as small as a typical electrode. When all electrodes are placed close to each other, however, spatial variety of leads can be lost and it makes the leads highly dependent on each other. Alternatively, if we separate these electrodes, we can trade complexity for spatial variety by separating electrodes and embedding them into different pads. Particularly, one lead is one pad with two/three electrodes. This requires introduction of at least two more pads to achieve spatial variety and dealing with consequent complexity. We need to ensure linear independence between the three corresponding leads.

### 2.2.2 Clinical Data

Two sets of data [11][4] are obtained from Dalhousie University. The first set includes 352 lead vectors for 352 nodes on the human torso derived from computer simulations. The second set includes coefficients for predicting the 352 nodes from EASI leads obtained through practical experiments and interpolations. Essentially, these two sets of data are representations of same leads in two coordinate systems: one is the heart dipole rectangular coordinate system; the other is the non-rectangular coordinate system spanned by leads ES, AS and AI. This data is used to derive the equation for transformation.

## 2.3 Derivation Based on Lead Vectors

If the lead vectors for three pads are $\overline{c_A}$, $\overline{c_B}$ and $\overline{c_C}$, according to (2), the potentials measured at the pads can be represented as:

$$V_A = \overline{c_A} \cdot \overline{p} \tag{4}$$

$$V_B = \overline{c_B} \cdot \overline{p} \tag{5}$$

$$V_C = \overline{c_C} \cdot \overline{p} \tag{6}$$

Combining the three measured potentials into a vector $\overline{V_3}$, and three lead vectors into a $3 \times 3$ lead matrix $\overline{\overline{c_3}}$, we have (7). This is illustrated in Figure 2.

$$\overline{V_3} = \overline{\overline{c_3}}\,\overline{p} \tag{7}$$

When the three lead vectors are linearly independent, the

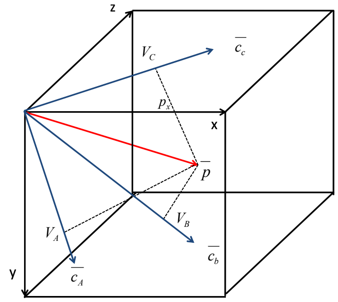


**Figure 2: Illustration of the heart vector and three lead vectors.**

heart vector can be computed as

$$\overline{p} = \overline{\overline{c_3^{-1}}}\,\overline{V_3} \tag{8}$$

The heart vector moment $\overline{p}$ can be computed from the three lead vectors if and only if $\overline{\overline{c_3^{-1}}}$ exists and is obtainable. It is not possible to fully represent cardiac activity by any single lead. At least three are necessary.

Once the heart vector moment is known, the 12-lead standard potentials can be computed by projecting $\overline{p}$ onto the corresponding 12-lead vectors. Take lead $V1$ for example. Combining (3) and (8), lead $V1$ can be computed as:

$$\overline{V_{V1}} = \overline{c_{V1}}\,\overline{\overline{c_3^{-1}}}\,\overline{V_3} \tag{9}$$

The same approach can be used to compute the other eleven leads in the conventional 12-lead system, which can be expressed in vector format as in (10), where each row in $\overline{\overline{c_{12}}}$ is a lead vector of the 12-lead system, and the same row in $\overline{V_{12}}$ is the electric potential measured.

$$\overline{V_{12}} = \overline{\overline{c_{12}}}\,\overline{\overline{c_3^{-1}}}\,\overline{V_3} \tag{10}$$

We rewrite (10) as

$$\overline{V_{12}} = \overline{\overline{T}}\,\overline{V_3} \tag{11}$$

We define $\overline{\overline{T}}$ in (11) as the transformation matrix, representing the transformation coefficients between two vectors, $\overline{V_3}$ and $\overline{V_{12}}$. The lead vectors needed for the matrix $\overline{\overline{c_{12}}}$ in (10) are directly available in the computer-simulation-based data set as mentioned above. The lead vectors for the three pads to compute $\overline{\overline{c_3^{-1}}}$ in Equation 10 are calculated by substracting two corresponding lead vectors, each of which is one node in the same data set.

Equation (10) provides a method of generating standard 12-lead ECG signals from 3-lead ECG signals. Specifically, if three electric potential traces are recorded at the three leads, traces for all 12-lead ECG can be synthesized.

### 2.4 Derivation Based on Coefficients from EASI Leads

Similar to (11), for an EASI lead system, we can obtain (12), where $\overline{\overline{U_{12}}}$ is equivalent to $\overline{\overline{T}}$ in (11), representing transformation coefficients from EASI leads to the 12 leads.

$$\overline{V_{12}} = \overline{\overline{U_{12}}}\,\overline{V_{EASI}} \tag{12}$$

Equation (12) can be extended to express the transformation from EASI leads to our three-pad leads as follows

$$\overline{V_3} = \overline{\overline{U_3}}\,\overline{V_{EASI}} \tag{13}$$

Combining (12) and (13), results in:

$$\overline{V_{12}} = \overline{\overline{U_{12}}}\,\overline{\overline{U_3^{-1}}}\,\overline{V_3} \tag{14}$$

Equation (14) is in the same expression as (10), but with different notations. The transformation matrices $\overline{\overline{U_{12}}}$ and $\overline{\overline{U_3^{-1}}}$ in (14) are counterparts of $\overline{\overline{c_{12}}}$ and $\overline{\overline{c_3^{-1}}}$ in (10) respectively. In essence, $\overline{\overline{U_{12}}}$ and $\overline{\overline{U_3^{-1}}}$ represent the corresponding transformation coefficients in the coordinate system spanned by EASI leads.

## 3. WIRELESS THREE-PAD ECG SYSTEM

Bringing two more wireless pads than signal-pad approach to W3ECG involves system design challenges as follows.

- (a) Latency and throughput of wireless communications of the three pads need to be guaranteed.
- (b) Sampling processes at the three pads need to be synchronized.
- (c) Pad placement locations need to be identified.
- (d) Distances between electrodes on each pad need to be standardized.

Challenge (a) has been studied in another paper [2]. We address challenges (b) and (c) in the following subsections, while the solution to challenge (d) is discussed in paper [3].

### 3.1 Topology

Wireless communications of three W3ECG pads are based on our proposed wireless body area sensor network quality-of-service provisioning framework [2]. The network is organized in a star topology and employs IEEE 802.15.4 beacon-enabled mode. This configuration makes it easy for both quality-of-service provisioning and synchronization purposes. A personal server coordinates communications between the three pads. Data can be stored locally at the personal server, forwarded to caregivers' database, or interpreted for real-time analysis. 12-lead ECG waveforms can be synthesized and presented based on the stored data.

### 3.2 Synchronization of Sampling Processes

The need to process data from three pads imposes the requirement to synchronize sampling processes at three pads. Equations (11) and (14) explain that the linear transformations are based on potentials recorded on each pad at the same moment.

The synchronization of sampling processes can be achieved by starting the sampling process at each pad at the same moment. Due to the drift of individual crystal oscillator on each pad, re-synchronization is needed periodically. Applying IEEE 802.15.4 beacon-enabled mode as the communications protocol, the time to start sampling and re-synchronization can be indicated by adding a payload in the beacon frame. The IEEE 802.15.4 superframe is an ideal structure for synchronizing both the communications and sampling processes. The reason to have the indications in the beacon-frame payload is that all nodes are required to be active when beacon frames are to be received, but they may be asleep during contention access periods.

## 3.3 Pad Placement Positions

Since the pad design has been standardized [3], they share the same amplification factor. Equations (10) and (14) can be used to synthesize the 12-lead ECG signals from observations on the three pads. The only requirement is that the corresponding vectors are linearly independent of each other.

### 3.3.1 Two Approaches

- Suggest one set of placement locations, and instruct the caregiver/patient to place the pads at exactly these locations. The popularity of EASI leads suggest the need to provide locations that can be easily identified in anatomy. In this case, the transformation matrix is unique and pre-calculated, and linear independence of leads is assured.
- Suggest sets of areas for placement, and instruct the caregiver/patient to place the pads at convenient locations. This approach caters to the needs of surgical operations, female users, or comfort of different individuals. A localization mechanism is needed to determine the pad placement locations during deployment, and to tune the coefficients in the transformation matrix in real-time. The system should give an indication if linear independence of leads is lost.

In the following, we study the first approach only.

### 3.3.2 Suggested Placement Locations

The pad placements are specified in Table 1 (The numbers in the table refer to node numbers in Dalhousie's BSM system model [9][11]).

| Pad Number | Input A | Input B |
|---|---|---|
| Pad 1 | 109 | 107 |
| Pad 2 | 170 | 127 |
| Pad 3 | 178 | 177 |

**Table 1: Suggested W3ECG pad placements.**

Ideally, each of the three pads is aligned with one axis of the heart vector. However, human organs and skin are not linear resistive components, which makes the alignment to the three axes difficult. The attempt to achieve orthogonality of three vectors leads to the above three placement locations, i.e., pad 1, pad 2 and pad 3 are placed according to the estimated directions of $x$, $y$ and $z$ in Figure 1.

As a result of the above placements, we obtain $\overline{\overline{\overline{U_3}}}$, which has a condition number of 2.6069 (EASI lead system has a condition number of 1.0162). It indicates a relatively stable linear transformation. In other words, it is tolerant to placement errors.

# 4. PERFORMANCE EVALUATIONS

## 4.1 Feasibility Test

In this section, we evaluate the feasibility of the above pad placement locations. ECG data collected by Dalhousie's BSM system for four patients [1] are examined. Acquired ECG data from these patients are with acute myocardial infarction. Because there were no pads actually placed on these locations, the signals that would appear on the three pads if we were able to place them there are calculated, based on how the differential signal is obtained on each bipolar lead.

We pick recorded potential values for nodes 170 and 127, 178 and 177, as well as 109 and 107 from [1]. Substractions between potential values of the two nodes in each of the pair, for each of the sampling time yield three time series of differential potential values that are then used in (14) to synthesis the simulated 12-lead ECG signals.

We compare the generated 12-lead ECG signals with the directly obtained version by evaluating the cross-correlation coefficients. Assuming the directly obtained signal is $V_i(t)$ ($i$ indicates the 12 different leads), and the synthesized signal is $V_i^{'}(t)$, then the cross-correlation coefficient $r_i$ can be represented as in (15), where $\overline{V_i}$ and $\overline{V_i^{'}}$ are means of $V_i(t)$ and $V_i^{'}(t)$ respectively.

$$r_i = \frac{\sum_t (V_i(t) - \overline{V_i})(V_i^{'}(t) - \overline{V_i^{'}})}{\sqrt{(\sum_t (V_i(t) - \overline{V_i})^2 (\sum_t (V_i^{'}(t) - \overline{V_i^{'}}))^2}} \qquad (15)$$

There are 12 coefficients for each patient. In order to prove the effectiveness of W3ECG's approach, these coefficients are shown in Figures 3 to 6 with those obtained by using the EASI approach, for each of the four patients, respectively.

From the above comparisons, we observe a good performance for our proposed W3ECG system for patients 2 and 4, but larger discrepancies for patients 1 (lead V4) and 3 (lead III). This coincides with those of the EASI system. We note for the EASI system, very small coefficients appear (0.3134 for lead V4 of patient 1 and -0.0850 for lead III of patient 3). However, other leads of patients 1 and 3 show high cross correlations in the EASI system. In comparison, having very small coefficients for some leads in the W3ECG system seems to have a negative effect on the other lead's performance, as we observe that lead II and aVF for patients 1 and 3 also experience small coefficients. This can be explained by the linear dependence our three pads may have on each other.

We also compare the waveforms of the original 12-lead signals and synthesized signals for patient 4 in Figure 8. It gives an idea of how close the waveforms appear for different leads. We note the signals for Lead III for both versions look quite similar in the QRS complex duration, although in Figure 6 we have a relatively smaller cross-correlation coefficient (0.7806). A high degree of similarity between original and generated waveforms also applies to Lead aVL, which has the second least cross-correlation coefficient (0.7983).

## 4.2 Experimental Studies

Setup for experimental studies are explained in [3]. Figure 7 presents the cross-correlation coefficients (calculated using (15)) for observed and synthesized 12-lead signals.

We have the following observations during the experiments. (a) Synthesized 12-lead signals exhibit almost the same QRS complexes as those of the observed versions, except Lead V2. The high correlations during QRS-complex duration make the corresponding 9 cross-correlation coefficients higher than 0.75 (1 coefficient between 0.5 and 0.6, 2

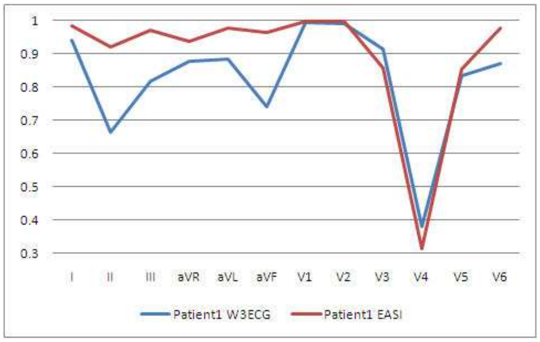


**Figure 3: Comparison of cross-correlation coefficients between W3ECG system and EASI system for Patient 1.**

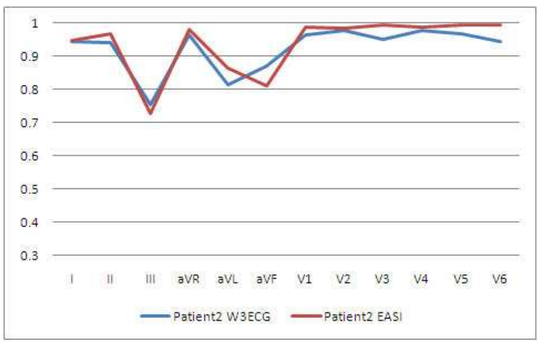


**Figure 4: Comparison of cross-correlation coefficients between W3ECG system and EASI system for Patient 2.**

coefficients below 5.5). (b) Two versions of signals show high degrees of similarity in the P-R segments, but large differences in S-T segments. (c) Synthesized 12-lead signals have amplified magnitudes, 1 to 4 times of those of the observed 12-lead signals.

## 5. CONCLUSIONS

Complementing a number of existing ECG systems, we provide caregivers and patients another choice: W3ECG. With the goal of designing a wireless ECG system to render caregivers standard 12-lead ECG information, we have added another two pads to wireless single-pad ECG systems to gain spatial variety during recording. The criteria for evaluating pad placements have been discussed and one possible set of pad placements has been provided. Feasibility tests of our selected pad placement positions show comparable results with respect to the EASI lead system. Experiment studies also exhibit high correlations between synthesized and directly observed 12-lead signals (9 out of 12 cross-correlation coefficients higher than 0.75).

We intend to further our research on improving pad placements and evaluating our proposed system over a larger pool of patients. Our long term goal is to develop a wireless multiple-pad system that works in such a way that the placement of the pads is not critical. As aforementioned, the placements of pads are important, but not unique. Intelligence can be provided to facilitate the placement of pads in real-time by computing the corresponding transformation matrix.

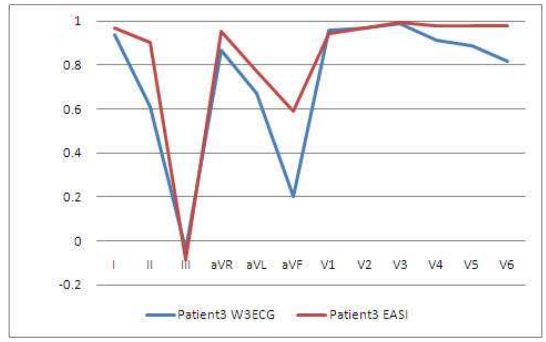


**Figure 5: Comparison of cross-correlation coefficients between W3ECG system and EASI system for Patient 3.**

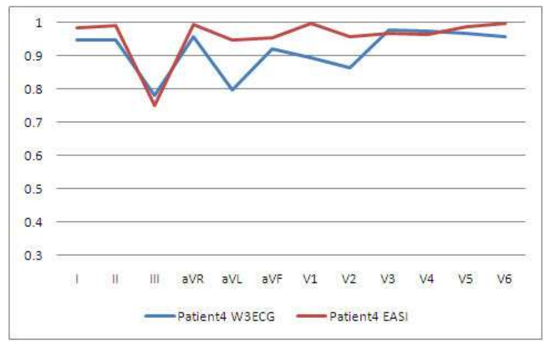


**Figure 6: Comparison of cross-correlation coefficients between W3ECG system and EASI system for Patient 4.**

## 6. ACKNOWLEDGMENTS

The authors would like to thank Prof. Horacek from Dalhousie University, Canada, for providing clinical data and guidance required to conduct this study.

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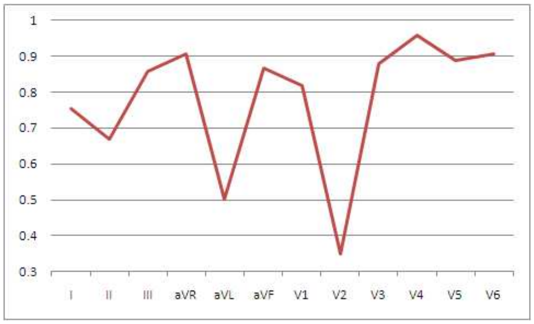


**Figure 7: Coefficients for cross-correlation between observed and synthesized 12-lead signals.**

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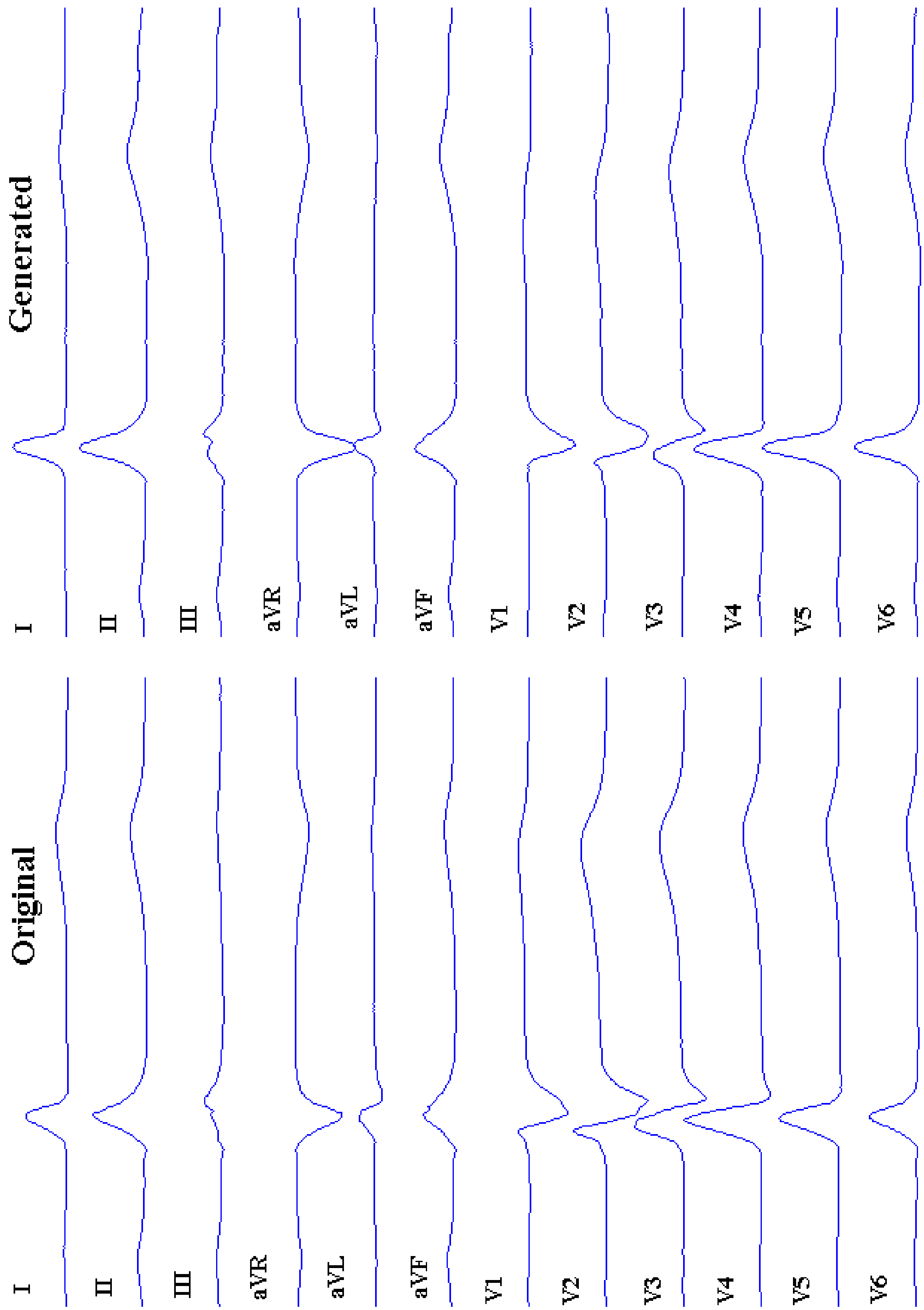


**Figure 8: Comparison between synthesized 12-lead ECG signals and directly obtained versions.**