Impact of Electrode Contact Site on the 12-Lead ECG Synthesized from Wrist-Worn Device Signals

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Abstract

This study explores the impact of electrode contact site on the accuracy of ECGs synthesized from two leads acquired using a wrist-worn device. Twenty-three patients with cardiovascular diseases and 32 healthy participants were involved in the study. To acquire ECG lead I, one electrode of the wrist-worn device was touched with the index finger of the opposite hand, while the other lead was obtained by contacting the electrode on the strap with a specific part of the body. Participants were instructed to touch areas on the body corresponding to the standard electrode placement sites for acquiring leads V3 and V5, as well as the abdomen. The 12-lead ECG was synthesized through a linear transformation of two leads from a wrist-worn device using personalized and universal transformation matrices. For both transformation matrices, the lowest RMS error between the reference and synthesized ECG was achieved for leads I and V1, regardless of the contact site from which the non-standard ECG was acquired. Among patients with cardiovascular disease, the RMS error ranged from 0.028 mV to 0.046 mV for lead I and from 0.024 mV to 0.036 mV for lead V1 when using a universal transformation matrix. The leads V2, V3, and V4 were synthesized poorly, as indicated by the twofold increase in the error. The contact site on the abdomen consistently yielded the lowest error for patients with cardiovascular disease.

1. Introduction

Despite the increasing interest in incorporating wrist-worn devices into healthcare, their full potential for identifying cardiovascular conditions has not yet been realized. While the latest generation of wrist-worn devices is capable of capturing a single-lead ECG, it remains insufficient for identifying certain heart conditions such as myocardial infarction. To address the limitation posed by the absence of a multi-lead ECG, researchers explored the feasibility of acquiring a 12-lead ECG sequentially either using portable accessories for smartphones [1] or smartwatches equipped with integrated ECG electrodes [2, 3]. However, sequential acquisition of single-lead ECGs introduces challenges such as time consumption and diagnostic errors from lead misplacement [4].

The latest wrist-worn devices can capture two ECG signals simultaneously [5]. One signal corresponds to lead I, while the other is non-standard, obtained between the wrist and a particular body site. Interpreting non-standard ECGs is impractical, making a comprehensible format, such as a 12-lead ECG, essential to render the information useful for clinician interpretation.

In this study, the feasibility of synthesizing a 12-lead ECG from the two signals acquired using a wrist-worn device is explored. Additionally, three contact sites of electrodes on the body are investigated to identify the site that allows for achieving the highest accuracy of the synthesized ECG.

2. Methods

2.1. Database acquisition

In total, 23 patients with a cardiovascular disease (CVD) and 32 healthy participants were enrolled in the study, see Table 1. The patients were recruited from inpatient wards of the Cardiology Department at Vilnius University Hospital Santaros Klinikos. Before participating, all eligible participants provided signed, written informed consent, adhering to the ethical principles delineated in the Declaration of Helsinki. Approval for the study was obtained from the regional bioethics committee under the reference number 158200-18/7-1052-557.

Table 1. Demographic and clinical characteristics of study participants.

	CVD patients	Healthy
Participants (women)	23 (5)	32 (17)
Age, yrs	59 $\pm$ 13	27 $\pm$ 6
Height, cm	174 $\pm$ 7	175 $\pm$ 11
Weight, kg	89 $\pm$16	72 $\pm$ 12
Body mass index, kg/m^2	29.3 $\pm$ 5.4	23.4 $\pm$ 2.7
CVD (#patients)		
Acute myocardial infarction	15	-
Right bundle branch block	4	-
Left bundle branch block	2	-
Atrial fibrillation	2	-
Myocarditis	1	-
Unspecified conduction disorder	2	-

The wearable wrist-worn device is equipped with three biopotential electrodes—one at its base, another at its upper end, and the last one on the strap. To record Einthoven lead I, one electrode is touched to the upper surface using the right index finger, while the other lead is acquired by touching the electrode on the strap to a specific part of the body. Participants were instructed to touch areas on the body corresponding to the electrode positions for acquiring standard precordial leads V3 and V5, as well as the abdomen 2 cm to the left at the level of the umbilical, denoted here as leads LA-V3, LA-V5, and LA-A, respectively. ECGs were acquired at a sampling rate of 500 Hz. Each recording lasted approximately one minute, with a minimum one-minute interval between separate recordings.

The standard 12-lead ECG, serving as a reference, was acquired at a sampling rate of 200 Hz using the Euroholter 12view recorder (Lumed, Italia). To align with the sampling rate of a wrist-worn device, the ECGs were resampled to 500 Hz. The ECGs from both the wrist-worn device and the reference ECG were filtered using a forward-backward high-pass filter with a cutoff frequency of 0.5 Hz and a low-pass filter with a cutoff frequency of 100 Hz.

2.2. Synthesizing a 12-lead ECG

The 12-lead ECG is synthesized through a linear transformation of two ECG signals from a wrist-worn device. The transformation matrix for synthesizing the 12-lead ECG is obtained by applying the Moore-Penrose pseudo inverse [6].

The first half of the ECG is used to create the transformation matrix, whereas the second half is used to assess the performance of both the personalized and universal matrices. A universal transformation matrix is obtained by averaging all personalized matrices, created separately for patients with CVD and healthy participants. Since wrist-worn device-based ECGs are of lower quality compared to conventionally acquired ECGs, an average PQRST complex was computed, with the QRS amplitude adjusted, and substituted with the corresponding average PQRST complex for each lead in each participant.

2.3. Performance evaluation

The accuracy of the synthesized 12-lead ECG is assessed by computing the RMS error E in milivolts (mV) between the leads of the reference and the synthesized ECG.

3. Results

Figure 1 presents the results obtained using personalized and universal transformation matrices for patients with CVD and healthy participants. The lowest E between the reference and synthesized ECGs is observed for leads I and V1, regardless of the acquisition site of the non-standard ECG. Among patients with CVD, the E values range from 0.028 mV to 0.046 mV for lead I and from 0.024 mV to 0.036 mV for lead V1 when using a universal transformation matrix. Conversely, the precordial leads V2, V3, and V4 were synthesized poorly, as indicated by the twofold increase in E. While the electrode contact site had minimal impact on E for healthy participants, the abdomen emerged as the most informative site for synthesizing the 12-lead ECG in patients with CVD.

Figure 2 illustrates the reference and synthesized ECGs for a patient with myocardial infarction using personalized and universal transformation matrices.

4. Discussion

Numerous attempts have been made to synthesize a 12-lead ECG from a reduced set, often as a subset of the standard 12-lead ECG [7]. Reduced lead systems have proven capable of capturing the information carried by the standard 12-lead ECG, as evidenced by the accurate diagnosis of cardiac abnormalities using the synthesized ECGs [8,9], especially when at least one precordial lead is included together with the Einthoven leads. While it is widely acknowledged that a minimum of three leads is required for adequate accuracy, attempts have been made to synthesize the ECG using only one lead through machine learning techniques [10–12]. While synthesizing the ECG from less than three leads results in information loss, it may still enhance interpretability compared to relying solely on one or two leads.

The main goal of this study was to examine how different contact sites affect the accuracy of the synthesized ECG. Consequently, the scope of the study was not to propose a new technique for lead synthesis. Therefore, a conventional linear transformation was employed, assuming that the heart-torso electrical system is both linear and

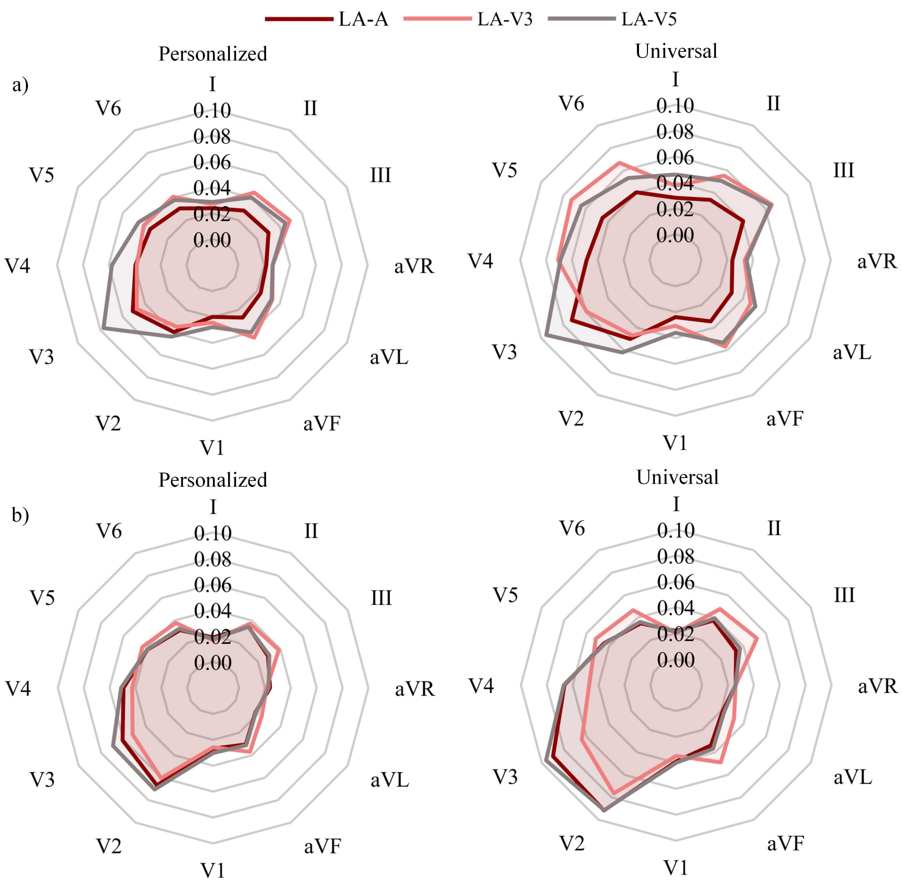

Figure 1. The RMS error E in milivolts between the reference and synthesized ECG for a) patients with CVD and b) healthy participants.

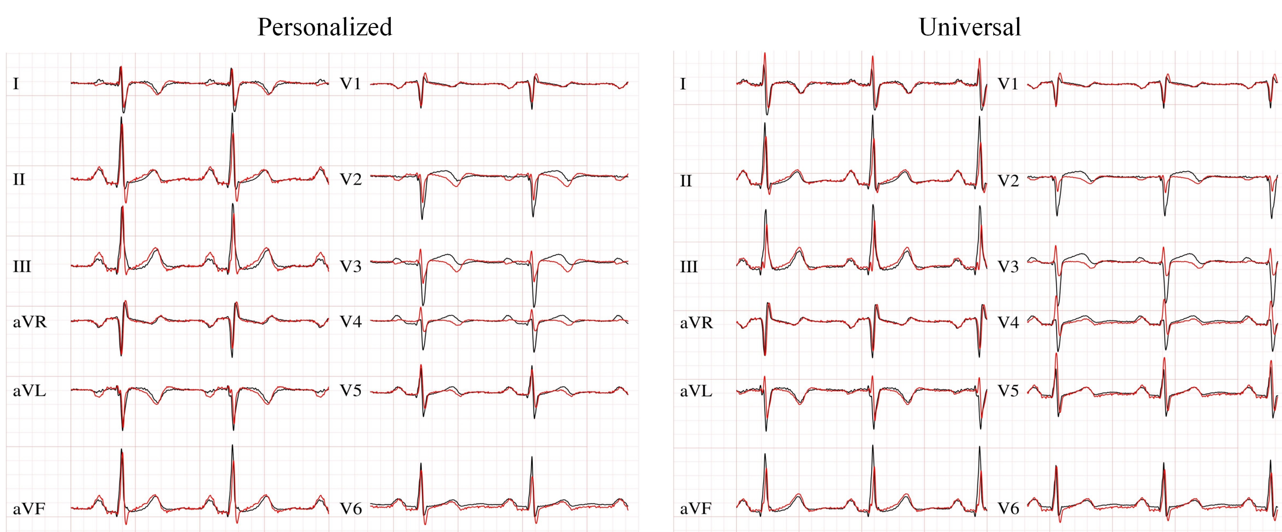

Figure 2. An example of reference (black) and synthesized ECGs (red) for a patient diagnosed with acute myocardial infarction using personalized and universal transformation matrices. The 12-lead ECG is synthesized from leads I and LA-A.

quasi-static. However, other types of approaches, such as those utilizing machine learning [10–12], may yield better performance, especially when considering the precordial leads.

In this study, we explored three body contact sites, although certain locations might have led to lower RMS errors, particularly when synthesizing precordial leads. Notably, previous research has pinpointed V2, V3, and V4 as the most informative for synthesizing the 12-lead ECG [11]. Our decision to focus on V3, V5, and abdominal contact sites was primarily driven by the fact that elderly individuals often experience restricted range of motion. As a result, we excluded the V1 and V2 contact sites due to difficulties encountered by some patients to reach and contact those body locations.

5. Conclusion

The study identified ECG leads I and V1 as the most accurately synthesized from two independent signals obtained using a wrist-worn device. Conversely, the approach proved less suitable for synthesizing V2, V3, and V4. Additionally, the study demonstrated that the anatomical location on the abdomen offers the most informative contact site for synthesizing the 12-lead ECG in patients with cardiovascular disease.

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