Detection of Electrode Interchange in Precordial and Orthogonal ECG Leads

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Abstract

This study presents methods for automated detection of interchanged precordial and orthogonal ECG leads that may prevent from incorrect diagnosis and treatment. For precordial leads V1-V6, correlation coefficients of QRS-T patterns and time-alignment of R and S-peaks are assessed. For orthogonal leads (X,Y,Z), analysis of QRS loops in the frontal plane, a set of correlation coefficients and a time-alignment of leads are implemented. The methods are elaborated using 15-lead ECG databases - 77 healthy control recordings from PTB database (training), and the total set of 1220 ECGs in CSE database with various arrhythmias (test). The specificity (Sp) for detection of the correct precordial leads configuration (V1 to V6) is 93.5% (training) and 91% (test) and the mean sensitivity (Se) for 23 simulated most common chest electrode swaps is 95.7% (training) and 95% (test). Sp for detection of the correct orthogonal leads X,Y,Z is 98.7% (training) and 93.3% (test), while mean Se for 47 reversals of electrode couples A/I, F/H, M/E is 98.5%, equal for both training and test databases.

1. Introduction

Misplacement of electrodes in multichannel electrocardiogram (ECG) is reported in 0.4-4% of all clinical recordings – a severe cause of erroneous diagnosis due to simulated false or concealed true ECG abnormalities [1]. The mobile e-health, which is advert as the biggest breakthrough in health systems improvement [2] raises the need for automated detection of electrodes interchange, considering the potential use of portable ECG devices by non-specialists.

Batchvarov et al. [3] review the most common cases for interchange of peripheral and chest leads and their effect on P-QRS-T patterns alteration, together with basic principles for detection of different leads reversals. Most of the published studies elaborate methods for limb leads analysis – recognition of left arm (LA) and left leg (LL) reversal by assessment of P wave amplitude [4] and analysis of QRS and P wave axes [5]; right arm (RA) – right leg (RL) swap alarm by search for flat line ECG in lead II [6]; detection of different LA/LL/RA reversals by direction of inscription of the P loop and/or the frontal P axis [7], analysis of the frontal QRS axis [8], comparison between a composed lead aVF/I and V6 [9], reconstruction of a lead using redundancy of information in the 8 independent leads [10]. Xia et al. [11] propose a combination of features from [5] and [10] to yield a more robust and accurate performance.

Much less studies are found to detect precordial leads reversals. Among above referred methods for limb leads interchange, only two analyse precordial leads – Hedén et al. [5] address 5 adjacent leads reversals (V1/V2, V2/V3, V3/V4, V4/V5, V5/V6), Kors and van Herpen [10] evaluate 9 leads reversals (5 adjacent leads and V1/V3, V4/V6, V4/V5/V6/V1/V2/V3, V6/V5/V4/V3/V2/V1). Recently, Dotsinsky [12] reports preliminary results for detection of 5 chest leads swaps (V1/V3/V2, V2/V1/V3, V4/V6/V5, V5/V4/V6, V1/V2/V4/V3/V5/V6) based on 2 criteria – absolute error of the middle lead vs. averaged sum of the surrounding leads; QRS amplitude evolution (increase from V1 to V3, decrease from V4 to V6).

Possibly because orthogonal ECG leads are seldom recorded in the clinical routine [13], no methods regarding the correct placement of the Frank orthogonal ECG leads (X,Y,Z) are found in the literature.

This study aims to present methods that may prevent from incorrect diagnosis and treatment by automated detection of precodrial and orthogonal leads interchanges.

2. ECG databases

This study uses ECG signals from two independent ECG databases – the publicly-available Physikalisch-Technische Bundesanstalt (PTB) diagnostic ECG database [14] and the Common Standards for Electrocardiography (CSE) database [15]. Both databases provide 15 simultaneously measured ECG leads (the conventional 12 leads together with the 3 Frank leads), sampled at 1000 Hz, 0.5 μV/LSB.

The developed methods for electrode interchange detection are trained with 77 ECG recordings from healthy controls in PTB and are tested with 1220 ECGs from CSE, containing various arrhythmias.

3. Methods

The methods for detection of precordial and orthogonal leads interchange are developed in Matlab (MathWorks Inc.). The preprocessing stage includes ECG filtering in the range (0.64-150) Hz, an automated detection of QRS boundaries [16] and selection of QRS-T pattern (QRS onset to QRS offset + 350 ms) of a normal/predominant beat within a 10-second episode.

3.1. Precordial leads interchange

We develop a method for detection of precordial lead swaps by assessment of 2 criteria over V1-V6:

- *Matrix R* (6x6) with correlation coefficients of the QRS-T patterns between each pair of leads:

$$R=\begin{bmatrix} r(V1,V1)=1 & >r(V1,V2) & >r(V1,V3) & >r(V1,V4) & >r(V1,V5) & >r(V1,V6) \\ r(V2,V1)< & r(V2,V2)=1 & >r(V2,V3) & >r(V2,V4) & >r(V2,V5) & >r(V2,V6) \\ r(V3,V1)< & r(V3,V2)< & r(V3,V3)=1 & >r(V3,V4) & >r(V3,V5) & >r(V3,V6) \\ r(V4,V1)< & r(V4,V2)< & r(V4,V3)< & r(V4,V4)=1 & >r(V4,V5) & >r(V4,V6) \\ r(V5,V1)< & r(V5,V2)< & r(V5,V3)< & r(V5,V4)< & r(V5,V5)=1 & >r(V5,V6) \\ r(V6,V1)< & r(V6,V2)< & r(V6,V3)< & r(V6,V4)< & r(V6,V5)< & r(V6,V6)=1 \end{bmatrix}$$

r(Vn,Vm) stands for the correlation coefficient between leads Vn and Vm, calculated as:

$$r(Vn,Vm)=\frac{\sum_{i=begin}^{end} Vn_i Vm_i}{\sqrt{\sum_{i=begin}^{end} Vn_i^2 \sum_{i=begin}^{end} Vm_i^2}},$$

where *i* is the sample number between *begin* (QRS onset) and *end* (QRS offset+350 ms).

Analyzing rows and columns of *Matrix R*, any deviation from the trend for gradual increase of the correlation coefficients towards the cell where a lead is compared to itself is suspected as incorrect lead.

- Time-alignment of positive R-peaks and negative S-peaks with monotonically increasing time-shift from V1 to V6 (see Figure 1).

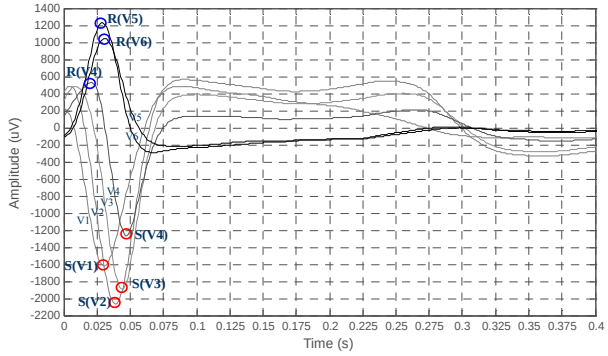

Figure 1. QRS-T pattern presenting the time-alignment of the high-amplitude peaks – S for V1-V4; R for V4-V6.

A threshold-based decision rule warns for precordial leads interchange when a number of suspicious *Matrix R* correlations and abnormal time-alignments is exceeded.

3.2. Orthogonal leads interchange

We develop a method for detection of Frank bipolar leads interchange based on 4 criteria over 15-lead ECG:

- Difference between the angles of the maximal vectors of the QRS loops in the frontal plane ([I,avF] vs. [X,Y]) – the angle difference is normally <60° (Figure 2).

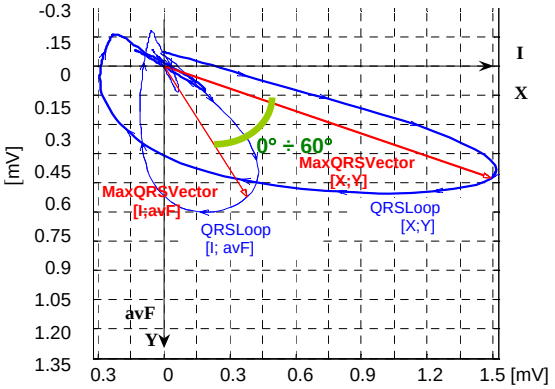

Figure 2. QRS loops in the frontal plane [I,avF], [X,Y]: Normal configuration for correct position of Frank leads.

- Correlation coefficients between measured leads and leads calculated from X, Y, Z by Dower transform (DT) – *r(I,I$_{DT}$)*, *r(II,II$_{DT}$)*, *r(V1-6,V1-6$_{DT}$)*. High correlations are expected for correct placement of X, Y, Z (Figure 3).

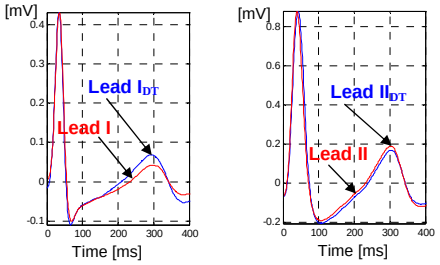

Figure 3. QRS-T pattern in I vs. I$_{DT}$, II vs. II$_{DT}$ for correct position of Frank leads.

- Correlation coefficient relations: *r(I,X)>r(I,Y)*, *r(V2,-Z)*>0 in normal configuration of X,Y,Z (Figure 4).

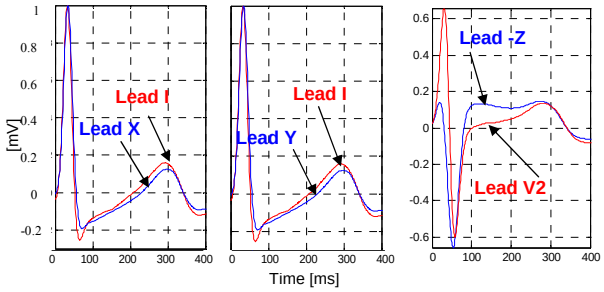

Figure 4. Lead I, vs. X,Y and V2 vs. -Z for correct X,Y,Z.

- Time-alignment of (Y,Z): the maximal positive peak in Y usually becomes apparent after the minimal negative peak in Z in normal configuration of X,Y,Z.

4. Results

The developed methods are tested by simulation of the following lead interchanges:

- Precordial leads: 23 different swaps between V1 to V6, including 2 adjacent leads reversals, and various interchanges of 3 and more leads. The simulated V1 to V6 swaps together with the obtained accuracy are presented in Table 1.
- Orthogonal leads: we are able to simulate 47 erroneous combinations of the Frank orthogonal leads, including full swap of X, Y, Z and polarity inversion (-X, -Y, -Z), the later simulating the reversal of the electrodes in the respective electrode couples A/I, F/H, M/E.

Table 1. Precordial leads interchange detection: accuracy calculated for the training and test databases. The first row (Test No0) shows the specificity for the correct combination of chest leads V1,V2,V3,V4,V5,V6. The following rows show the sensitivity for 23 different precordial leads swaps (highlighted in grey).

Test No	Precordial Leads						Training PTB 77 files Accuracy (%)	Test CSE 1220 files Accuracy (%)
	V1	V2	V3	V4	V5	V6		
	Grey cells show the swapped electrodes							
0	V1	V2	V3	V4	V5	V6	93.5	91.8
1	V2	V1	V3	V4	V5	V6	100	90.7
2	V1	V3	V2	V4	V5	V6	98.7	90.6
3	V3	V1	V2	V4	V5	V6	100	96.6
4	V1	V2	V4	V3	V5	V6	100	94.6
5	V1	V2	V3	V5	V4	V6	88.3	91.3
6	V1	V2	V3	V4	V6	V5	77.9	84.6
7	V1	V2	V3	V6	V4	V5	85.7	93.9
8	V6	V2	V3	V4	V5	V1	100	98.9
9	V3	V2	V1	V4	V6	V5	100	99.3
10	V3	V2	V1	V4	V5	V6	100	93.9
11	V1	V4	V3	V2	V5	V6	100	96.8
12	V1	V2	V5	V4	V3	V6	100	97.7
13	V1	V2	V3	V6	V5	V4	83.1	93.0
14	V4	V2	V3	V1	V5	V6	100	97.5
15	V1	V5	V3	V4	V6	V2	100	99.0
16	V1	V2	V6	V4	V5	V3	97.4	97.6
17	V5	V2	V3	V4	V1	V6	100	98.8
18	V1	V6	V3	V4	V5	V2	100	99.1
19	V3	V4	V1	V2	V5	V6	100	98.9
20	V1	V4	V5	V2	V3	V6	100	99.3
21	V1	V2	V5	V6	V3	V4	100	98.0
22	V4	V5	V6	V1	V2	V3	77.9	90.2
23	V6	V5	V4	V3	V2	V1	94.8	84.9
Se-mean (Test No 1 to 23)							**95.7**	**95.0**

Table 2. Orthogonal leads interchange detection: specificity for correct X,Y,Z (Test No0), sensitivity for 47 erroneous X,Y,Z combinations (Test No 1 to 47).

Test No	Input Frank bipolar Leads			Training PTB 77 files Accuracy (%)	Test CSE 1220 files Accuracy (%)
	X	Y	Z		
	Grey cells show not correct Frank leads				
0	X	Y	Z	98.7	93.3
1	-X	Y	Z	100	99.9
2	X	-Y	Z	94.8	92.5
3	X	Y	-Z	77.9	83.2
4	-X	-Y	Z	100	100
5	X	-Y	-Z	100	100
6	-X	Y	-Z	100	100
7	-X	-Y	-Z	100	100
8	X	Z	Y	96.1	91.1
9	-X	Z	Y	100	100
10	X	-Z	Y	100	94.2
11	X	Z	-Y	100	98.6
12	-X	-Z	Y	100	100
13	X	-Z	-Y	81.8	89.7
14	-X	Z	-Y	100	100
15	-X	-Z	-Y	100	100
16	Y	X	Z	79.2	88.3
17	-Y	X	Z	100	100
18	Y	-X	Z	100	100
19	Y	X	-Z	100	99.5
20	-Y	-X	Z	100	100
21	Y	-X	-Z	100	100
22	-Y	X	-Z	100	100
23	-Y	-X	-Z	100	100
24	Z	X	Y	100	99.3
25	-Z	X	Y	100	99.9
26	Z	-X	Y	100	100
27	Z	X	-Y	100	99.9
28	-Z	-X	Y	100	100
29	Z	-X	-Y	100	100
30	-Z	X	-Y	100	99.9
31	-Z	-X	-Y	100	100
32	Y	Z	X	100	99.4
33	-Y	Z	X	100	100
34	Y	-Z	X	100	99.9
35	Y	Z	-X	100	99.8
36	-Y	-Z	X	100	99.8
37	Y	-Z	-X	100	99.5
38	-Y	Z	-X	100	100
39	-Y	-Z	-X	100	100
40	Z	Y	X	100	96.1
41	-Z	Y	X	100	99.7
42	Z	-Y	X	100	100
43	Z	Y	-X	100	99.4
44	-Z	-Y	X	100	100
45	Z	-Y	-X	100	100
46	-Z	Y	-X	100	98.8
47	-Z	-Y	-X	100	100
Se-mean (Test No 1 to 47)				**98.5**	**98.5**

5. Discussion and conclusions

In this study we present methods for automated detection of precordial and orthogonal leads interchange which may prevent both ECG readers and conventional ECG interpretation programs from misdiagnosis and improper treatment. The methods are trained and tested over two independent datasets that provides unbiased accuracy reported for the test dataset.

The performance of our method for precordial leads interchange detection is compared to the results reported in [5,10,12] – see Table 3. The specificity (Sp) for correct placement of V1 to V6 as reported in [5,10] is about 8% higher than Sp achieved in this study (99.9% vs. 91.8%). Besides, the mean values of sensitivity (Se) for swapped configurations of precordial leads as reported in [5,10,12] are in the range 71.8% to 93.3%, while our method is outperforming with mean value Se-mean=95%. Although a decade ago a higher Sp was mandatory [10], the rapid progress in distant ECG registration and interpretation with potential use of portable ECG devices by persons with different amount of training becomes a precondition for more frequent errors, and therefore raises requirements for higher Se. The comparative study in Table 3 suggests that methods based on correlations between leads ([10], the presented method) are favorable in respect to Se than methods which rely only on conventional ECG measurements, such as amplitudes, areas and axes [5,12]. The most difficultly detected reversals of precordial leads are swaps between two adjacent leads V2/V3, V5/V6, as well as V4/V6.

Table 3. Precordial leads interchange detection: performance of our method vs. published studies for the test databases. The values of Sp, Se-mean, Se-range are shown as reported by the authors, replaced by '-' mark where missing.

Study	Sp (%)	Se-mean (%)	Se-range (%)	Lead reversal with min(Se)
Our	91.8	95	84.6 to 99.3	V5/V6
[5]	99.9	71.8	44.5 to 83	V2/V3
[10]	99.9	93.3	78 to 99.3	V4/V6
[12]	-	87	-	-

This study presents the first report of a method for detection of orthogonal leads interchange with Sp of 93.3% (correct X, Y, Z configuration), and Se of 98.5% (mean value), 83.2 to 100% (min-max range) for all simulated 47 configurations of swapped Frank leads. It appears that the polarity inversion of Z-lead (Test No3: X,Y,-Z) is the most difficultly detected configuration with minimal Se of 83.2%. The relatively rare clinical use of orthogonal ECG leads predisposes to low experience and higher probability for human errors in lead arrangement.

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