Could Determination of Equivalent Dipoles from 12 Lead ECG Help in Detection of Misplaced Electrodes

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Abstract

The purpose to participate in the PhysioNet Challenge 2011 was to test our recent computational techniques that might help in assessing of the misplaced ECG electrodes.

ECG recordings from the Challenge data sets were analyzed in three steps. First, general characteristics of the recorded signals were determined. Second, cluster analysis was applied to obtain templates that helped to estimate the quality of individual beats, and to isolate the background signal, used for signal drift determination. Finally, equivalent dipoles were determined and used to reconstruct the template. Since its precision depends on the exact location of the lead locations, we speculated that by varying the lead locations to minimize error (optimization) the actual lead location could be detected. We found that the method is reliable to detect correctly placed leads, and less reliable in recognizing different swaps. For the PhysioNet/CinC Challenge 2011 we obtained a score of 0.818.

1. Introduction

The aim of the PhysioNet/Computing in Cardiology Challenge 2011 was to develop an efficient algorithm able to run in near real-time within a mobile phone that can provide useful feedback to a layperson in the process of acquiring a diagnostically useful ECG recording. At a minimum, the software should be able to indicate within a few seconds, if the ECG is of adequate quality for interpretation. Ideally, the software should identify common problems and either compensate for these deficiencies or provide guidance for correcting them.

Our preliminary tests using the training set provided by the Challenge 2011 [1] and also our own data have shown that in case of low amplitude signal, the acceptability of the recording does not depend only on the absolute value of the artifacts but also on the signal to noise ratio. Hence, in our strategy we adopted that each ECG recording should provide at least one acceptable beat that appears in all leads simultaneously to contain all information necessary for ECG diagnosis. To find whether the beat is acceptable, the template was necessary to obtain.

Additionally, our interest has been focused to the detection of misplaced electrodes. For this purpose we adopted our method for determination of equivalent dipoles from the multiple surface ECG recordings [2]. The algorithm was based on the rationale that ECG signals measured on the surface of the body are produced by current sources inside the body and depend on ECG lead locations on the body surface as well as on the geometrical and conductive properties of the body. It enabled to reconstruct the surface signals, but with certain error.

We speculated that if one of the lead were displaced, current dipoles could still be determined, but when reconstructing the surface signal the error would increase, assuming the correct initial lead locations. On the other hand, if we were able to reduce error by displacing leads, they would move toward to correct location. If the displacement were big enough to change the order of electrodes on the body, it would be considered as misplaced electrodes. It would occur, e.g. if the lead V3 appeared left to the lead V2 after optimization procedure

2. Methods

The challenge data represented 500 recordings of the standard 12-lead ECG (leads I, II, III, aVR, aVL,aVF, V1, V2, V3, V4, V5, and V6) with full diagnostic bandwidth (0.05 through 100 Hz), and with the leads recorded simultaneously for a minimum of 10 seconds; each lead is sampled at 500 Hz with 16-bit resolution.

Besides general characteristics of measured signals, our analysis included identification of individual beats and theirs component (P, QRS, and T wave), cluster analysis, and the construction of the templates for each cluster found. Individual beats were compared to the template to determine the norm, a parameter representing the quality of individual beats and its components. Iteratively, the norm was used to purify the template, and as criterion whether the beat is acceptable or not. In a 10 sec long ECG recording, it was further requested that in an acceptable recording there are at least 3 good beats. All ECG recordings were analyzed as follows.

2.1. General characteristics of the signal

The raw signal was filtered to provide two additional signals: a high pass signal above 45 Hz for detection of 50-60 Hz noise and other high frequency e.g. due to muscular tremor and a low pass signal below 3 Hz for detecting signal drift and baseline wandering. Both were obtained using. the recursive 4^{th} order Chebyshev filters. In this step, we used only 8 of 12 signals, omitting thus leads III, aVR, aVL,aVF, since they represent linear combination of the leads I and II and hence contain no additional information. For each signal used we calculated ADC off-set value, rms voltages of the raw, low frequency and high frequency signals

2.2. Cluster analysis and the template

Individual beats and their position were identified, and the cluster analysis was performed to identify possible different types of beats e.g. due to multifocal ventricular activity To perform cluster analysis, signals were decomposed using PCA in the region containing individual beats and the biggest three decomposed signals were used to obtain a recomposed signal based on their vector sum. Then, the cross-correlation function was applied mutually to all individual recomposed signals to find the most similar beats. Up to two different kinds of beats were recognized. Besides recognizing different types of beats, this technique also enabled to reject similar, but noisy or distorted beats. Then template beats were constructed for each cluster found.

2.3. Individual beat characteristics and the quality of beat

Each individual beat was compared to the template in the region of the P, QRS and T wave and for each of them the amplitude, the time shift (the essential part of e.g. QTV), and the norm were determined [3]. The first two properties were later used in the construction of the background signal, whereas the latter was used to determine the quality of each individual beat. The norm was defined for each beat segment (P, QRS, and T wave) as an average of the integrated rms deviation of each individual beat segment from the template one, normalized with amplitude of that segment.

2.4. The background signal

Template beats that were adjusted for individual beat characteristics (changing P, QRS or T wave time shift, beat wave amplitude) were subtracted from the raw signal at the appropriate trigger point to provide the background signal, which was considered to be absent of any ventricular electrical activity.

The background signal was created for each lead and was used for estimation of the signal drift, and to check the quality of template determination.

2.5. Detection of misplaced electrodes

Using the template signals, we applied our method for determination of equivalent dipoles in a bounded spherical conductor [2], and adopted it for 12 lead ECG. The precordial leads were assumed to be located at the standard positions of the chest, which was approximated with a spherical surface to fit the region of the precordial leads, whereas in case of the extremity leads, the VR, VL and VF signals were used, located initially on the same spherical surface but initially in the frontal plane through the center of the thorax. Thus, 9 signals were used in analysis, 6 precordial (V1, V2, V3, V4, V5, and V6) and three unipolar extremity leads (VR, VL, VF).

The template signals were divided into small intervals of 20 ms, each displaced by 5 ms in the region of the QRS and T wave and then decomposed into principal signals (PC). The biggest two PC signals from each small interval were then used to construct a set of equivalent dipoles [2] applying an inverse algorithm and using an optimization method. Here, each equivalent dipole was determined independently of others at the minimum of its objective function. Thus, the template signals were approximated by a sequence of equivalent dipoles.

To determine the precision of this approximation, we used the above representation to reconstruct the template signal. Then, the difference between the measured and reconstructed signals represented error of determination. In our case we used the rms error, and called it lead error.

Since this error also influenced by the torso lead locations, we speculated that by varying lead locations to minimize the error (optimization) the actual location of the lead could be detected. However, this problem represents a huge computational task for optimization of 9x3 coordinates (three for each lead used), and we tried to reduce it using two measures. First, it was not the complete template that was used in the calculation of the lead error of, but only its six segments of 20 ms length. The selection of segments was based on the amplitude of signals obtained by PCA, and anisotropic distribution of equivalent dipoles in 3D space. Since each 20 ms segment was represented by 2 equivalent dipoles, there were 12 dipoles to be determined for each lead location. Second, in order to facilitate the determination of the extremity lead misplacement, the initial location of extremity leads started from 8 different settings: six represented all permutations of the extremity lead placements, VL, VR and VF for left arm (LA), right arm (RA) and left leg (LL), respectively, and two for the right leg (RL) replacement with RA or LA. In this notation, VR-VL swap would present RA-LA misplacement.

The lead rms error was calculated for each of the 8 initial lead settings, and that one with the lowest error determined the positions of the extremity leads. Then, for the selected lead placement, the procedure was followed by optimization of all lead locations in two steps. First, the Simplex method using the Nelder-Mead algorithm [4] was applied separately for each of nine leads to get a provisional value, and the old location was replaced with an average of the old and the provisional one. Then, a gradient based method (Gauss-Newton) [5] was used, for which the function derivatives were calculated from the function evaluations in the two adjacent points.

2.6. The scoring system

A score defining acceptability of the recording was constructed in 3 steps. In the first step, general characteristics of the raw or any of the used filtered signals were investigated. Each recording was divided into segments of 1s length, and for each segment and each of the 8 leads considered, we calculated ADC off-set values, rms voltages of the raw, low frequency and high frequency signals (all in microvolts) with the following critical values:

- ADC off-set > 8 mV
- 50-60 Hz rms noise > 0.150 mV
- Rms voltage of the raw signal >1 mV
- Rms voltage of the low frequency signal > 1mV

If the any of the critical values below was exceeded, then that segment was considered as unacceptable. In case of more than 30% of unacceptable segments, the recording was considered unacceptable having the score equal the number of bad signals, but limited by 10.

If the score after the first step was still 0, the second step were applied, using characteristics of individual beats as well as the signal noise. We evaluated several parameters all related to each individual beat with the following critical values separating acceptable values from the unacceptable ones:

- Beat ADC off-set > 2 mV or 2000 units
- Beat 50-60 Hz rms noise > 0.150 mV
- Beat drift >1 mV
- Beat drift > 2.5*QRS amplitude >
- Beat drift > 5* T wave amplitude
- T wave norm > 0.2
- QRS norm > 0.125
- QRS amplitude < 0.1mV if occurred in more than 4 leads. All units are microvolts except the norm in the relative units.

In the scoring system, the value of each parameter was divided by its critical value and multiplied by 10. Thus, its score was proportional to the parameter value and equal 10 at its critical value. Each parameter was calculated for each beat and each lead. Then we selected beats to be accepted in further evaluation. Each individual beat was accepted, if any of the above properties had its score below 10. If more that 2/3 of beats satisfied this condition, the rest of the beats were treated further to get a characteristic weighted value that favors bad beats. We used a nonlinear exponential weighting function. Thus, for the parameter x with individual values x_i, we first calculated the sum $y = \sum(\exp(x_i)-1)$ over all accepted beats, and then its inverse logarithmic value $x_{mean}= \ln(y+1)$. We repeated this procedure three times, first over all accepted beats for each parameter, each lead, anf over all leads, and finally over all parameters used. This resulting score was added to -9, so when it was equal of greater than 10, it produced the final score 1 or greater.

In the third step, we tested for possible misplaced leads. For a single swap, the final score was set to 2 (or 4 for a double swap), neglecting thus information obtained from the second step.

2.7. Lead misplacement study

In a separate study, we recorded 12 lead ECG in four persons from 60 to 85 years (two healthy, one LBBB and one right axis deviation, with different QRS and T spatial angles), in all with a normal lead setting, and with 5 mutual swaps of the extremity leads (RA-LA, RA-LF, LA-LF, RA-RF, and LA-RF swaps. For all possible lead settings we calculated the lead error, and identified the lead placement on the basis of the lowest error value.

3. Results

For the PhysioNet/CinC Challenge 2011 we obtained our best score of 0.818 or 409/500 correct guesses. Of the total 500 cases, 330 were acceptable and 170 unacceptable. In this particular evaluation we did not considered all individual beat characteristics (background signal drift, norm). In another evaluation, when we introduced the quality of beats, the result did not change considerably (0.79), but the number of acceptable recordings (295) was reduced by 35 on the account of unacceptable ones (205). It suggests that the reduction of acceptable recordings occurred due bigger consideration of individual beat characteristics, and that at least some apparently acceptable recordings were not acceptable using additional criteria..

In the lead misplacement study, the normal lead placement was detected in 3 of 4 cases (75%), whereas misplaced leads were detected in 11/20 cases (Table 1). Specifically, misplacement was detected correctly in all cases of RA-LA and RA-LF swap, and failed to be detected in the LA-LF swap, which was usually misplaced with the normal lead setting. As the correct lead detection was accompanied by similar equivalent dipole characteristics (location, spatial orientation) in all correct lead placements, suggesting that in that case the method already provides the solution for misplacement., .

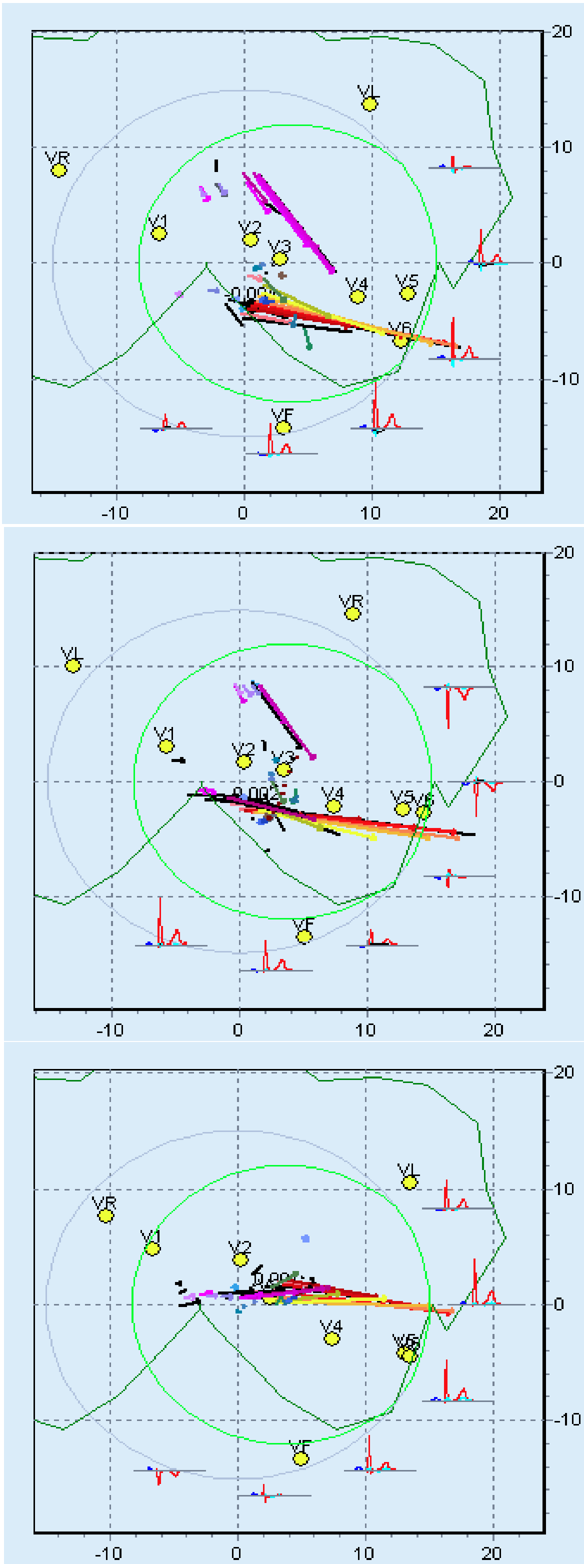

Figure 1. Lead locations (open circles) and equivalent dipoles (solid lines) in the frontal plane Top: no misplacement. Middle: RA-LA swap (leads VR and VL). Bottom: LA-LL swap (leads VL and VF). ECG signals aVL, I,-aVR, II, aVF and III from top-right to down-left.

Table 1. Statistics of misplaced lead detection

Lead placement	Detected misplacement	Correct detection	Common misplacement
Normal	3	3	LA-LF
RA-LA swap	4	2	RA-LA-LF
RA-LF swap	4	2	RA-LA-RF
LA-LF swap	0	0	Normal
RA-RF swap	3	1	Normal
LA-RF swap	0	0	Normal

4. Discussion and conclusions

As the number of acceptable recordings may change if considering individual beat characteristics that includes analysis of the ECG waveforms, it suggests that the quality of beat should participate in the decision whether the recording is of adequate quality for interpretation.

We have also shown that determination of equivalent dipoles might help in detection of misplaced leads. Though, the method has shown some potential, it still has to increase reliability. One explanation seems to arise from the information content of the ECG recording in the frontal plane, provided by only two independent signals. In order to solve this issue, an additional independent signal, e.g. RA-RF would be very helpful.

Further study that includes different ECG patterns is necessary for evaluation of the method.

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