Recognition of Diagnostically Useful ECG Recordings: Alert for Corrupted or Interchanged Leads

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Abstract

The upgrade of mobile phones with applications for acquisition, pre-processing and transmitting the patient's ECG to a hospital unit would be of great benefit for prevention against the most frequent mortality caused by heart failure. This idea is promoted by the Computing in Cardiology Challenge 2011, which encourages the development of algorithms for analysis of the ECG quality within few seconds, aiming to warn about diagnostically unacceptable recordings. This paper presents an algorithm for scoring the noise corruption level by evaluation of ECG amplitude dynamics, baseline wander, powerline interference, EMG and peak artifacts. The score achieved for participation in Event1 is 0.908. Additionally unacceptable ECGs with interchanged leads are detected with sensitivity of 96.8% (30/31 files) for peripheral leads and 87% (40/46 files) for chest leads.

1. Introduction

When conditions during ECG acquisition are not rigorously controlled, ECG quality is highly susceptible to external noisy components and other distorting factors which might impede the reliable manual or automated measurements, or hazard the correct diagnosis. Automatic management of large amount of ECGs by analytical quality metrics is shown to improve the quality of ECG annotations reducing human review and costs [1,2].

During the years, members of our team are contributing towards development of methods for improving the ECG quality by filtering the main sources for ECG corruption - powerline interference (PLI), baseline wander (BLW) and electromyographic (EMG) noise. The main goal is to maximally preserve the useful ECG components, commonly overlapped with noises. In this respect, the subtraction procedure eliminates PLI with amplitude and frequency deviation without affecting the ECG spectrum [3]; the BLW bi-directional high-pass recursive filter [4] is optimized towards adapting the cut-off frequency with respect to the frequency components of the ECG signal [5]; the approximation filtering with dynamically varied number of samples and weighting coefficients in respect to the ECG slope, is preserving sharp QRS forms with a considerable reduction of the EMG noise [6]; the 'linearly-angular' procedure for EMG suppression is applying smoothing filtration outside the QRS complexes, and moving averaging inside them with restoration of the sharp Q, R and S peaks [7].

Misplacement of electrodes in 12-lead 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 [8]. Batchvarov et al [9] review the effect of the most common cases for interchange in peripheral and chest leads on P-QRS-T patterns, together with some algorithms for their detection. Specific cable interchanges or ECG abnormalities might disturb the correct detection.

The presented method detects noise corruption and leads interchange for recognition of diagnostically useful ECGs in the Computing in Cardiology Challenge 2011.

2. ECG dataset

The study uses the Challenge 2011 dataset available from PhysioNet [10], including 10-second recordings of standard 12-lead ECGs (sampled at 500Hz, 5μV/LSB resolution, full diagnostic bandwidth 0.05–100Hz). The dataset comprise signals related to common problems which might appear when people with varying amounts of training are recording ECG via disposable or suction cup electrodes connected to mobile phones (misplaced electrodes, poor skin-electrode contact, not connected electrode, PL interference, artifact resulting from patient motion, etc.). Reference annotations of the ECG quality in the context of 'acceptable' or 'unacceptable' recording for diagnostic interpretation are accessible for the challenge in non-blinded and blinded mode:

- Training Data (Set A) with non-blinded annotations, including 773 acceptable and 225 unacceptable ECGs;
- Test Data (Set B) with blinded annotations, including 500 ECGs.

Misplaced electrodes have been manually identified in 74/1498 recordings, publicly available in the list [11].

3. Method

The system for recognition of diagnostically useful 12-lead ECGs is developed in Matlab (MathWorks Inc.). It implements a combination of algorithms which first aim at assessment of the noise corruption level and second at detection of interchanged peripheral and/or chest leads.

In a preprocessing stage, automatic detection of QRS boundaries is applied [12]. A reliable QRS detection is achieved by using the lead with the best amplitude dynamics within the range mean±standard deviation.

3.1. Scoring of the noise corruption level

Specific algorithms are applied for assessment of the noise corruption levels by analysis of ECG amplitudes and slopes in different frequency bands. The list of all implemented noise tests is as follows:

(1) Detection of low amplitude (LoA) or lead saturation – the amplitude dynamics is evaluated at:

- $Range_{10s}$: peak-to-peak amplitude of the signal within 10s.
- $Range_{QRS}$: peak-to-peak amplitude of the signal between QRS boundaries after 4Hz high-pass filter.

(2) Detection of PLI – the outputs of two band-pass filters BP50 (48-52Hz) and BP60 (58-62Hz) are estimated. Two measures of PL noise levels are calculated:

- RMS_{BP50}, RMS_{BP60}: Root mean square noise of BP50 and BP60 outputs measured outside the QRS boundaries;
- SNR_{BP50}, SNR_{BP60}: signal-to-noise ratio between the QRS amplitude and BP50 and BP60 outputs.

(3) Detection of BLW – the output of 1Hz low-pass filter is used to calculate two BLW measures:

- MAA_{BLW}: mean absolute amplitude of BLW;
- MAD_{BLWRR}: mean absolute deviation of BLW estimated for the sequence of beat-to-beat intervals.

(4) Detection of EMG and other high-frequency (HF) noises – the output of 20Hz high-pass filter is used to evaluate the HF content by RMS amplitudes inside and outside QRS boundaries – $MaxRMS_{HF}$ and $MinRMS_{HF}$, respectively. The HF noise level is defined as:

- $SNR_{HF} = MaxRMS_{HF}/MinRMS_{HF}$.

(5) Detection of peak artifacts (PA) – the output of 1Hz high-pass filter is evaluated to detect PA by the criterion:

- SL_{PA}: Slope (mV/ms);

The PA detection is validated when PA periodicity due to pacemaker (PM) or steep QRS is not discovered:

- PM detector: 50% of all artifact-to-artifact intervals are distanced >750 ms and have variance <40ms;
- QRS detector: the variance of the artifact-to-artifact intervals <20% in at least 50% of the strip.

Each noise test is performed independently. The ECG is processed in a sliding window over the 10-second strip to measure the noise levels in each lead. For each window the highest noise level among leads is reported. The window with the lowest noise estimation is considered as the best candidate for diagnostic interpretation. Its noise measures are compared to preset thresholds which imply for acceptable quality of the ECG recording. When a threshold is exceeded, presence of specific noise is alert. The sum of all alerts is used for scoring the noise corruption level.

3.2. Detection of interchanged leads

Misplaced electrodes are detected by analysis of the P-QRS-T patterns in all leads using two independent tests – for chest leads and for peripheral leads.

(1) Detection of peripheral leads interchange

The method implements common rules for P-QRS-T amplitudes and polarities in I, II, III observed in normal ECG [9] improved by additional verification of I and aVF with V6 [13]. The principles of the later are based on the assumption that V6 is a chest lead lying in the frontal plane at about 30° rotation from the X-axis and it can be compared to a composed lead aVF/I with module $M = \sqrt{aVF^2 + I^2}$ and direction $\tan\alpha = aVF/I$. Minimal differences between V6 and aVF/I are detected for the correct position of right arm (RA), left arm (LA) and left leg (LL) electrodes compared to the five possible limb electrode reversals. To make conclusions using V6, it is necessary to verify that V6 is correctly placed (using algorithm (2) below). The rotation of the neutral electrode on right leg (RL) with RA and LA is easily captured by low QRS amplitude (<100 μV) in I, II or III.

(2) Detection of chest leads interchange

Gradual progression of the P-QRS-T pattern is expected from V1 to V6 projection of the normal ECG dipole. This progression is evaluated by the correlation between V1 to V6 when compared to each other. The correlation coefficient *r* is calculated as follows:

$$r = \frac{\sum_{i=begin}^{end} S1_i S2_i}{\sqrt{\sum_{i=begin}^{end} S1_i^2 \sum_{i=begin}^{end} S2_i^2}},$$

where *S1* and *S2* are the signals in the compared leads; *i* is the sample number between *begin* (QRS onset) and *end* (QRS offset+350 ms).

A second criterion evaluates the time and amplitude alignments of the S and R peaks from V1 to V6 which also follow gradual progression.

The decision for electrode interchange is not considered for ECGs with conduction disturbances seen as wide QRS (>120ms), mostly negative V1-V6, rapid (>120bpm) or paced rhythms. Besides, the confidence is improved by confirming the electrode interchange for more than 80% of the P-QRS-T patterns in the 10s strip.

4. Results

The developed system for recognition of diagnostically useful 12-lead ECGs is tested in 2 steps.

In a first step only the algorithm for scoring the noise corruption level is applied, considering that ECGs with electrode interchange are part of the acceptable set in the final annotations. For the training dataset, we achieve specificity of 97.8% (correct 756/773 acceptable ECGs) and sensitivity of 81.8% (correct 184/225 unacceptable ECGs). For the test dataset, the received score for the Challenge Event1 (closed source, open data) is 0.908. The detection of different noises is addressed in Figures 1-5.

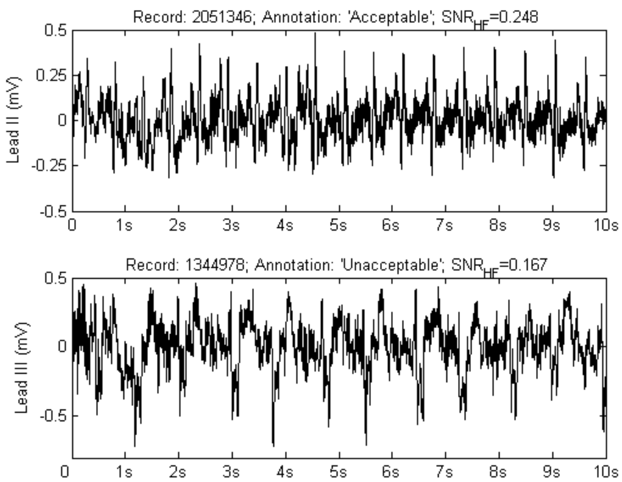

Figure 1. The close HF noise levels in the acceptable and unacceptable records are border cases for adjustment of the HF noise threshold.

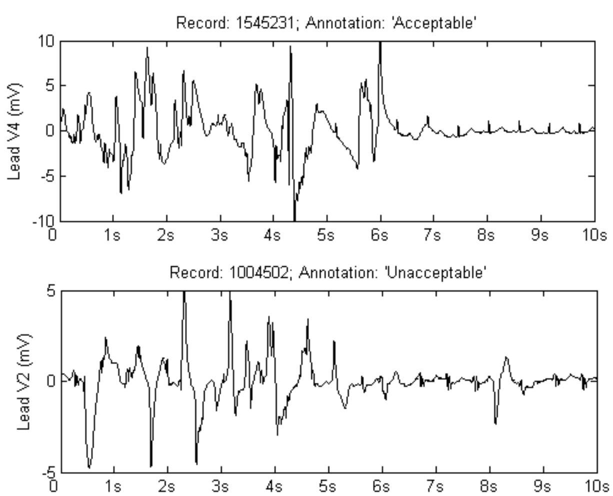

Figure 2. Peak artifacts are detected in both traces but clean signal is available during about 3s in the acceptable record and more than 4s in the unacceptable record. This discrepancy implies either for other hidden cause of unacceptable quality or for inconsistent criteria applied by the annotators.

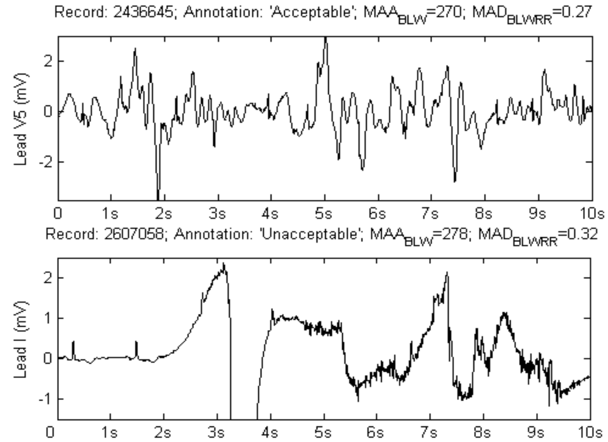

Figure 3. The close BLW measures in the acceptable and unacceptable records show the indiscernible difference between both. Doubtful annotation of the acceptable record is suggested due to its considerable distortion.

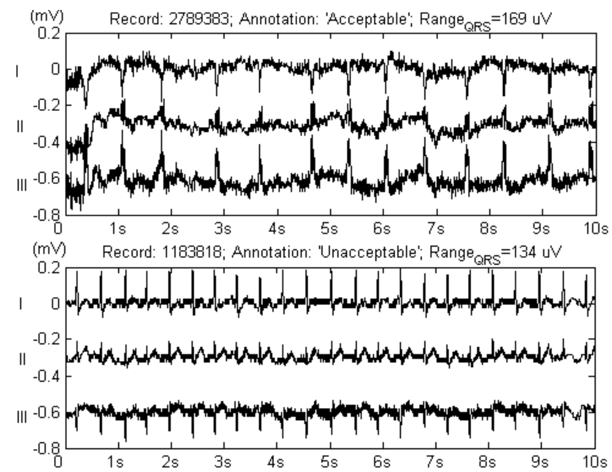

Figure 4. The amplitude dynamics in both records is a border example for adjustment of the LoA threshold.

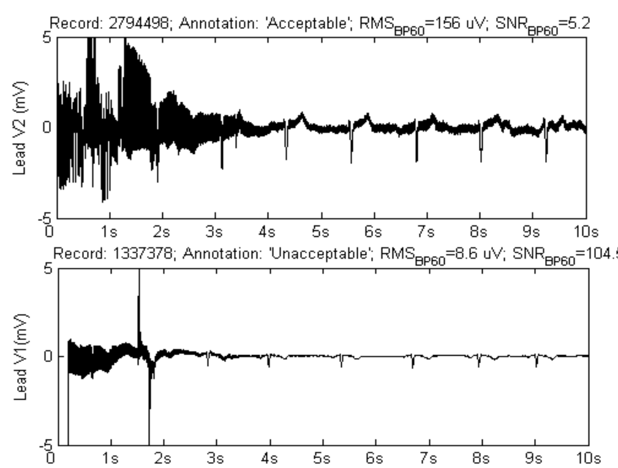

Figure 5. PLI measures in the acceptable lead are more unfavorable than in the unacceptable (the worst among 12 leads). This embarrasses the PLI detection criteria setting.

In a second step only the detection of electrode interchange is tested, considering the posted list [11] with manual annotations of ECGs with misplaced electrodes in both training and test datasets. The sensitivity is 96.8% (30/31 files) for detection of misplaced peripheral leads and 87% (40/46 files) for chest leads. Examples for correct detection are shown in Figures 6-7.

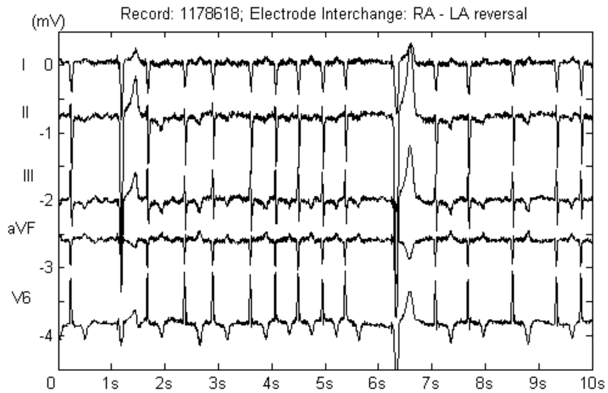

Figure 6. The algorithm for peripheral electrodes detects lead reversal I=–I, II=III, III=II corresponding to RA-LA rotation validated for 85% of the QRS.

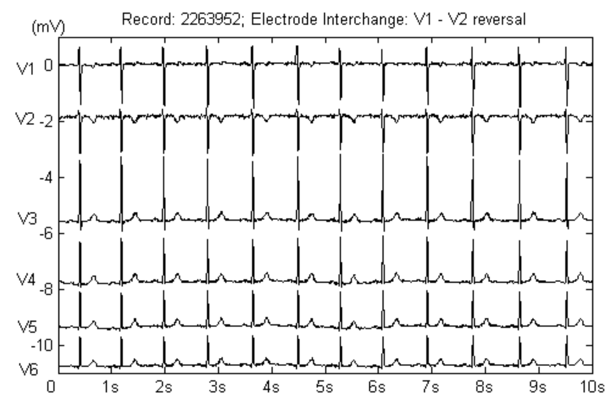

Figure 7. Based on assessment of the correlation of V1 to V6, V1-V2 reversal is detected for 100% of the QRS.

5. Discussion and conclusions

The noise levels corrupting the ECG components in different frequency bands could be considered as reliable measures of the ECG quality. In this respect, the presented algorithm evaluates the BLW influence at frequencies below 1Hz, PLI in a band ±2Hz around the central PL frequency, EMG above 20Hz, QRS amplitude dynamics above 4Hz. PA covering steep artifacts from different sources are estimated in a wide frequency band above 1Hz. The thresholds for the defined noise measures, the duration of the window for their estimation and the scoring of leads with significant noise impact are iteratively adjusted until the best accuracy of 94.2% (940/998) is achieved for the training database. Due to the different proportion of acceptable (77.5%) and unacceptable (22.5%) records, the performance is shifted towards higher specificity (Sp=97.8%) than sensitivity (Se=81.8%). We consider that the inconsistent criteria of the human annotations for acceptable and unacceptable quality (examples in Figures 2,3,5) embarrass the setting of universal thresholds but rather application-specific adaptation would be necessary in future.

Tests on the heterogeneous ECG cohort in this study show that detection of peripheral leads misplacement is reliable at 96.8%, however, identification of chest leads misplacement is more difficult with sensitivity of 87%.

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