Assessment of Signal Quality and Electrode Placement in ECGs using a Reconstruction Matrix

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Abstract

We estimate that as much as 5% of all recorded ECGs worldwide may, to some degree, suffer from poor signal quality or incorrect electrode positioning, which often interferes with correct interpretation of the ECG. Proper training of ECG technicians and regular inspection of signal quality is necessary to achieve a high standard. Due to the large amounts of ECGs recorded daily, we devised an automatic ECG quality inspection method based on the conversion of an ECG into a VCG and back again into a reconstructed ECG. Incorrectly placed electrodes as well as different types of noise can be detected with a high level of accuracy.

We used this method to assess the quality of the ECGs in the learning set of the Physionet/Computing in Cardiology Challenge 2011, giving a correct interpretation of the quality of the ECGs of 92.2% which corresponded to a sensitivity of 97.0 and a specificity of 75.1%

1. Introduction

Yearly over 50,000 ECGs are recorded and stored in an digital database in our hospital. Extrapolating this number conservatively, we estimate a lower limit of 20,000,000 ECGs being stored yearly worldwide in any electronic form. The quality of these recordings is dependent on the training of the technicians, the involvement of the reviewer / overreader and the quality of the equipment. We estimate that as much as 5% (1,000,000) ECGs exhibit some form of quality problem and that in 1% the quality is strongly interfering with the correct interpretation of the ECGs and/or the speed of the interpretation process.

The majority of the low quality recordings are due to bad electrode contact or due to incorrect electrode positioning. Both issues can be addressed by better instruction of the technicians and a daily check of the signal quality, but the sheer number of recordings prohibits visual inspection of all ECGs.

The Physionet/CinC Challenge of 2011 addressed a very similar problem: to automatically inform the technician who has just recorded an ECG in a remote location if the ECG is of sufficient quality to be analyzed after telephonic transmission to a hospital. Therefore, we set out to develop a method that predicts, with high accuracy, whether a given ECG is acceptable or unacceptable for further interpretation. We also restricted ourselves to a method that wouldn't need to detect the individual P, QRS or T complexes, and be independent of any morphological abnormalities in the ECG. Preferably, this method should be able to detect not only excessive noise in a recording, but also electrode reversals like the very common left-right (L/R) arm electrode switch, the right arm-neutral (R/N) switch, and the left arm-left foot (L/F) switch. All these switches have a profound impact on the ECG and, hence, on the interpretation thereof.

Since no information is lost in a L/R switch and such a switch should be obvious to a trained observer, who can mentally correct the inverted I and the switched leads II/III on the one hand and aVR/aVL on the other hand, it may be argued that such ECGs are acceptable.

The R/N switch causes loss of information since the lead that is determined by the R and F electrodes (II) is now measured from right leg to left leg, resulting in an almost straight line whereas the R-L combination (I) now resembles –III.

The L/F switch results in a switch of the leads I and II while lead III becomes inverted, -III. Although this switch may mimic, under certain circumstances, an old inferior infarction, such a switch will go undetected most of the time.

An R/F switch is of no consequence since voltages at right and left ankle are almost equal.

Electrode placement according to Mason and Likar [1], although giving a right shift of the electrical heart axis and therefore not suitable for standard ECGs [2], is probably undetectable.

2. Methods

The CinC 2011 Challenge ECGs were stored in 8 lead format (independent leads I, II, V1-V6). The length of the recording can be variable but was, for this study, kept at 10 s with a sample frequency of 500/s.

Transformation of an ECG into a VCG was done using the 3x8 Kors Matrix (KM) developed by Kors et al [3]. X, Y and Z are constructed as the sum of the products of the amplitudes in all 8 leads and their coefficients. X, Y and Z are as defined by the AHA: X and Z lie in the transverse plane, X pointing towards the left side of the patient, Z towards the back. Y is perpendicular to the transverse plane, pointing downward.

Table 1. Kors matrix.

Lead	X	Y	Z
I	0.38	-0.07	0.11
II	-0.07	0.93	-0.23
V1	-0.13	0.06	-0.43
V2	0.05	-0.02	-0.06
V3	-0.01	-0.05	-0.14
V4	0.14	0.06	-0.2
V5	0.06	-0.17	-0.11
V6	0.54	0.13	0.31

Back transformation of the VCG into the reconstructed ECG was done by either the 8x3 quasi-inverse of the Kors Matrix (IKM) or by an optimized inverse matrix (OIM). Optimization was done by concatenation of 180 ECGs into a single ECG matrix with 900,000 rows by 8 columns. Next we post-multiplied with Kors' 8x3 matrix to obtain VCG=ECG*K. Finally, we regressed ECG on VCG. The resulting 3x8 OIM is such that VCG*OIM is the linear transformation of VCG that best approximates ECG in the sense of least squares. For both methods an 8x8 matrix can be constructed by multiplying the original KM with any of the 2 inverse matrices. The 8x8 matrix resulting from multiplication of the KM and the OIM is termed the Direct Transformation Matrix (DRM), table 2.

The linear correlation between the original ECG and the reconstructed ECG was calculated with the Matlab (The Mathworks, Natick, MA, USA) 'corr' function. Performance of the two methods was tested on a subset of the ECGs present in the learning set of the 2011 CinC Challenge. This subset exists of 775 ECGs that, according to a panel of 3 experts, were acceptable for overreading by a physician [4].

Checking for electrode placement according to Mason and Likar [3] was performed on a set of 180 ECGs recorded on a Case 8000 (GE Medical Systems, Milwaukee, WI, USA) recorder with the capability of simultaneously recording 3 additional leads. From these recordings a set of standard (STD) ECGs and a set of ECGs according to Mason and Likar (ML) were constructed (each 8 leads/10 s).[4].

Checking for L/F electrode swaps was done by generating 8-lead ECGs in which columns 1 and 2 were exchanged. Here also the subset of 775 acceptable ECGs from the CinC Challenge 2011 was used, except those that were identified as having an L/R electrode switch.

Optimizing the cutoff values for distinguishing between acceptable and unacceptable ECG quality in the learning set was done by the Goal Seek function in Microsoft Excel with maximization of the total number of correctly identified ECGs. Only ECGs with correlations above the cut-off points in all leads were considered to be acceptable.

Table 2. Direct Reconstruction Matrix

Lead	I	II	V1	V2	V3	V4	V5	V6
I	0.3	-0.02	-0.28	-0.06	0.16	0.37	0.4	0.29
II	-0.25	0.95	0.09	-0.31	-0.08	0.11	0.08	0.18
V1	-0.13	0.06	0.46	0.74	0.56	0.23	-0.07	-0.14
V2	0.04	-0.01	0.04	0.14	0.15	0.12	0.06	0.03
V3	0	-0.04	0.14	0.3	0.24	0.12	0.01	-0.04
V4	0.08	0.09	0.11	0.36	0.41	0.35	0.2	0.1
V5	0.07	-0.16	0.1	0.36	0.3	0.18	0.06	-0.02
V6	0.39	0.2	-0.58	-0.56	-0.11	0.38	0.58	0.5

3. Results

3.1. Performance

Performances of the DRM and the KM/IKM methods were compared, see table 3. Especially leads I, V1, V2 and V5 showed a remarkable improvement with the DRM method. Hence, we used the DRM method for all subsequent calculations rather than the KM/IKM method. An ECG with the two reconstruction methods is shown in figure 1.

Table 3. Average correlations for ECG-reconstruction

Lead	KM/IKM	DRM	P
I	0.667	0.773	< 0.001
II	0.922	0.945	< 0.01
V1	0.537	0.874	< 0.001
V2	0.586	0.773	< 0.001
V3	0.839	0.851	0.156
V4	0.865	0.885	0.031
V5	0.538	0.868	< 0.001
V6	0.902	0.909	0.208

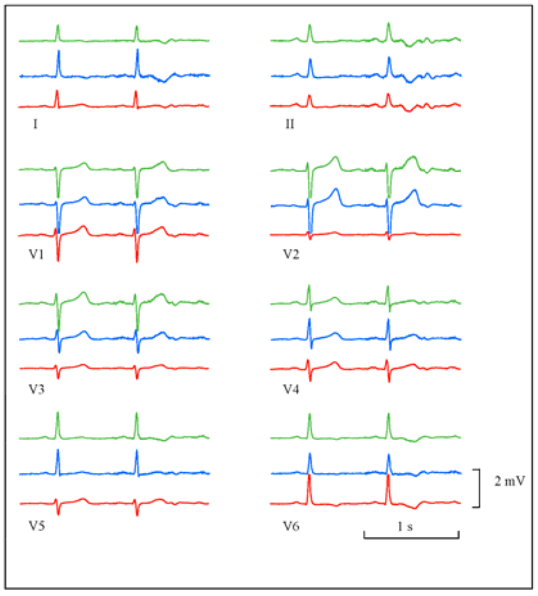

Figure 1. Example of an original ECG (blue, middle signal) with reconstruction methods KM/IKM (red, bottom signal) and DRM (green, top signal). The signals correspond to the first 2 s of ECG 1013179 from the learning set.

3.2. Challenge

Using the DRM method for the determination of acceptable vs. unacceptable ECG quality, we calculated correlations for each of the 8 leads in all 1000 ECGs belonging to the learning set. Using the cut-off values of table 4 (optimized for a maximal score) we found an overall correct prediction of 92.2%, a sensitivity of 97.2 and a specificity of 75.1%

Table 4. Optimized cut-off values

Lead	Optimal cut-off
I	-0.97
II	0.61
V1	-0.1
V2	-0.5
V3	0
V4	-0.95
V5	-0.9
V6	0.37

3.3. Electrode switches

L/R electrode switch: Of the 23 correlations in lead I with values < -0.25 (21 in the acceptable set, 2 in the unacceptable set), 3 were due to the presence of an electronic pacemaker and 20 were due to inversion of lead I. Only 3 inversions were detected at higher correlations.

L/F electrode switch: of the 752 ECG that were tested after removal of the ECGs suspect for L/R electrode switch, 540 showed a higher correlation in lead V2 in the correct ECG than in ECGs with the artificially introduced L/F switch, corresponding to 71.6% accuracy. However, if the same test was done on the subset of 180 STD ECGs from the STD/ML experiment, V1 correlations were performing slightly better, 75.6%. Table 5 shows the performance of all leads for both sets.

Table 5. Percentage of ECGs with correctly identified L/F electrode switches. 23 L/R switches were excluded form the 775 learning set ECGs.

Lead	Learning set	STD subset
I	55.2	66.1
II	44.6	54.4
V1	57.3	75.6
V2	71.6	70.6
V3	46.4	67.8
V4	42.4	52.2
V5	41.4	51.1
V6	43.5	46.1

R/N electrode switch: we found only 3 suspect ECGs within the learning set. Since none of the leads in any of these 3 ECGs showed any extreme correlation, we decided not to pursue our investigations into this electrode switch using the DRM.

Mason-Likar electrode positioning: Compared to a standard ECG, an ECG recorded according to the method of Mason and Likar shows a rightward shift of the electrical heart axis (ref), generally caused by a decrease in the R wave in the leads I, aVL and an increase in R waves in leads II, aVF and III. If, even after this shift, the electrical heart axis remains in the normal range, the incorrectly recorded ECG will go undetected. Even so, in 161 of the 180 simultaneously recorded ML and Standard ECGs, the correlations in lead I were larger for the standard than for the ML recorded ECGs, but they never got below any of the 8 cut-off points described in table 4.

4. Discussion

Although the method described here was not tested against the 500 ECG test set from the CinC 2011 Challenge, we think that the simplicity of the test itself, checking for low correlations using the redundancy in the ECG and thereby focusing both on electrode switches and noise, without the need for QRS detection, has it's merits. The method takes full advantage of the fact that e.g. the vectorcardiographical lead X is constructed from I (0.38) and V6 (0.54) - see table 1. If left and right arm electrodes are switched, lead I will invert and lead X will be greatly changed, as will the reconstructed ECG be. Also, excessive amounts of noise in these leads which will render the ECG unacceptable for analysis, results in low correlations. For the Challenge, however, we set the cut-off value for the correlations in lead I at -0.97 in order to include ECGs with L/R electrode switches into the acceptable set. If one would like to deem L/R switches unacceptable, the cut-off value could be raised to -0.25.

Unfortunately, the method is not suited for R/N electrode switches, but since these R/N switches always result in an unmistakably flat line in lead II, other methods can easily take care of these switches (e.g. determination of maximal and minimal amplitudes).

For L/F switches, V2 is a good discriminator since it performs quite well in detecting those switches, both in the CinC 2011 Challenge learning set and the STD/ML set obtained in our own department. It involves a simple extra step, by calculating not only the ECG under investigation, but also one for the ECG with leads I and II exchanged. The fact that V1 performs better on the STD/ML set (75.5% of the L/F switches detected) is probably due to the much more controlled recording conditions than the CinC Challenge set. Since the majority of the ECGs will be recorded under conditions that resemble the CinC Challenge set, V2 will be, after all, the better choice.

Finally, Mason-Likar recordings generally exhibit lower correlations than the standard ECGs, but the DRM method is, as of yet, not applicable to distinguish between the two methods.

References

[1] Mason RE, Likar I. A new system of multiple-lead exercise electrocardiography. Am Heart J 1966 Feb;71(2):196-205

[2] Practice Standards for Electrocardiographic Monitoring in Hospital Settings, Drew BJ, Califf RM, Funk M, Kaufman ES, Krucoff MW, Laks MM et al. Circ. 2004; 110:2721-46

[3] Kors JA, van Herpen G, Sittig AC, van Bemmel JH. Reconstruction of the Frank vectorcardiogram from standard electrocardiographic leads: diagnostic comparison of different methods. Eur Heart J 1990, 11(12):1083-1092

[4] Moody GB. The PhysioNet/Computing in Cardiology Challenge 2011: Improving the Quality of ECGs Collected Using Mobile Phones. Computing in Cardiology 2011; 38 xxxx-xxxx

[5] Man SC, Maan AC, Kim E, Draisma HH, Schalij MJ, van der Wall EE, et al. Reconstruction of standard 12-lead electrocardiograms from 12-lead electrocardiograms recorded with the Mason-Likar electrode configuration. J Electrocardiol 2008; 41:211-9.

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