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The development and validation of an early warning system to prevent the acquisition of 12-lead resting ECGs with interchanged electrode positions

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Abstract

Background: A fraction of routine resting ECG's are taken with electrode positions interchanged, leading to possible clinical misinterpretation.
Objective: Develop and test a method to detect and prevent electrode reversals at the electrocardiograph before the ECG is acquired.
Method: The algorithm is based on QRS axis and P amplitudes for limb electrode reversals, and P-Q-RS amplitude distances to detect chest electrode reversals. The evaluation method involved a large (>18,000) hospital database for which serial ECG's were available and was based on simulated juxtapositions.
Results: The 7 most common lead reversals could be detected with a specificity of 99.8% per type and an average sensitivity of 90%, excluding LA-LL reversal (22% sensitivity).
Discussion: Results are similar to retrospective studies that used smaller, more homogeneous datasets.
Conclusion: The early warning system reduces the ECG's recorded with reversal by 80%, at the price of a modest false alert rate of 1.4%.

Keywords: Electrocardiogram; ECG; Electrode reversal; Electrode interchange; Electrode misplacement; Automatic detection

Introduction

Correct electrode positions are important for the interpretation of 12-lead resting ECGs. The most frequent position errors are those of the chest electrode with respect to the anatomical landmarks of the body and juxtapositions of electrode leads. This work is about the latter; it describes a method to detect lead reversals in real time and to evaluate its performance.

The frequency of occurrence of electrode juxtapositions is not well known; estimates vary between 0.4% and 4% of all ECGs taken [1]. Interchanges occur between limb electrodes (e.g. left arm versus right arm) and in the order of the chest leads (e.g. V2, V1, V3 instead of V1, V2, V3). Mistaking chest lead wires for limb lead wires is less likely because of color coding and the usually different length of the wires.

Many ECGs with lead reversals are not detected by routine interpretations, giving rise to possible inaccurate diagnoses [2,3]. Computer interpretation programs traditionally only attempt to detect a right arm–left arm switch (although more electrode reversal cases have been added recently), but do not attempt to "correct" this situation, and only give a warning.

Several algorithms for retrospective recognition of electrode interchanges have been published. Hedén and coworkers [4] developed and tested a method based on artificial neural networks, first only for right arm–left arm reversals, subsequently also for other limb and chest electrode reversals [5]. Kors and Van Herpen [6] developed a method based on the correlation between the taken ECG lead and its reconstruction from the other 7 independent leads. Xia et al. [7] retested both of these algorithms on different data and also developed a method that combined criteria from both.

The objective of our study is to develop and test a method to reduce the number of ECGs taken with lead reversals by giving an alert to the technician for possible lead reversals before the ECG is finalized.

Materials and methods

Algorithm

During the observation period, when electrodes are connected and the ECG technician is waiting for the signal to stabilize, a running average of the P–QRS–T complex is maintained over 10 seconds. This complex is constantly analyzed for a lead reversal, and a warning is given on the

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screen of the electrocardiograph to check the electrode positions if a possible lead reversal is detected, in a manner similar to the warning that an electrode is not connected. The ECG technician has the possibility to ignore the warning and take the ECG anyway. When the technician presses the "Take ECG" button, the last 10 seconds is analyzed and stored. In this manner, the lead reversal detection algorithm does not add any time to the standard procedure of taking ECGs.

The algorithm has been developed to detect the reversals described in Table 1.

No attempt has been made to detect right leg–left leg reversals, because the effect on the ECG of this reversal is minimal and clinically insignificant. Also, non-neighbor chest lead reversals are not considered; they would trigger a neighbor reversal detection anyway, and the purpose of the algorithm is to detect a switch, not to precisely identify it.

Because of the low prior probability of a switch, the algorithm has been designed to have a high specificity while maintaining a reasonable sensitivity. The objective is to detect the majority of the lead reversals, without giving too many nuisance messages that would interrupt the ECG technician's work flow unnecessarily, and potentially lead to the reversal messages being ignored.

ECGs with a ventricular pacemaker rhythm are ignored by the algorithm. The absence of the P-wave and the unusual QRS morphology of many pacemaker ECGs would lead to more false positives than justified for the purpose, considering the low percentage of pacemaker ECGs in routine clinical practice.

The detection of RA–LA lead reversal relies on QRS axis, P amplitude, and lead I and V6 being very dissimilar. Similar, albeit less sensitive rules were developed for detection of LA-LL and RA–LL reversals. For precordial leads, a matrix was calculated of the P, Q, R, and S amplitudes and additional waveform data for each lead. The distances between the leads in this multidimensional space were then calculated. Call this distance Dij. In normal conditions, that is, no electrode interchange, you would expect the distance value between leads from neighboring electrodes to be the smallest. So the rule for, say V3–V4 exchange detection is $D23 > D24$ and $D45 > D35$. In other words, something is wrong if V2 appears to be closer to V4 than it is to V3 and simultaneously, V5 appears to be closer to V3 than to V4. However, if V3 and V4 are interchanged these inequalities are to be expected. Obviously, only half of this rule can be used for the V1–V2 and V5–V6 reversals since there are only neighbors at one side.

Table 1
Table of electrode reversals taken into account by the algorithm.

Limb leads	Chest leads
Right arm–left arm: RA–LA (R–L)	V1–V2 (C1–C2)
Left arm–left leg: LA–LL (L–F)	V2–V3 (C2–C3)
Right arm–left leg: RA–LL (R–F)	V3–V4 (C3–C4)
Left arm–right leg: LA–RL (L–N)	V4–V5 (C4–C5)
Right arm–right leg: RA–RL (R–N)	V5–V6 (C5–C6)
Right arm –right leg + left arm–left leg: Ar–Lg	

In parentheses are the IEC denominations of the electrodes. Throughout the article, the AHA denominations will be used.

Validation

The algorithm was evaluated using a large database of recorded ECGs from a medium size university hospital. The database contained circa 250,000 ECGs of a mix of out-patients and hospitalized patients that were recorded between February 2003 and April 2012. The database was cleansed on the basis of non-ECG parameters to remove test records, unidentified patients and patients with discrepancies or idiosyncrasies in demographic data (e.g. non-matching ID number and name in serial ECGs, unusual IDs, names with non-alphanumeric characters).

Subsequently, patients were selected who had at least three ECGs in the database that were taken on different days, forming three groups of ECGs, circa 20,000 ECGs each. These ECGs were exported from the database. All ECGs were then analyzed for the presence of decoding errors, missing leads and the presence of a "pacemaker" call in the automatic interpretation. If any of these conditions occurred, all three ECGs of that patient were removed. A total number of 18,654 ECG triplets remained for final processing. The ECGs were processed by the same lead reversal algorithm as in real time on the electrocardiograph. The ECGs from the database were 10 seconds in length, the same duration used in real time for the construction of the running average P–QRS–T complex. Of the three groups, one was used for performance analysis, and the other two were used for comparison as explained below.

In order to assess the specificity of the algorithm, it is necessary to separate the true from the false positives. True positive lead reversals were found in a two-stage process. First, all cases with positive lead reversals for which a reversal was also found in one or both of the comparison ECGs of the same patient were considered false; it is highly unlikely that a real electrode reversal would have occurred twice on different days. Then, all other positive cases were reviewed by an expert. The two serial ECGs were presented together with the test ECG as an aid to confirm the expert's judgment, which was particularly helpful for limb lead reversals. Using the serial ECGs, most of the time there was little doubt whether a reversal had taken place, as any experienced ECG reader will confirm. Whenever the reviewer was in doubt, the call was considered to be false, based on the low prior probability of a true reversal. A limb lead reversal call was considered true also if the reviewer was of the opinion that a different limb reversal had taken place than called by the algorithm, e.g. if the algorithm called RA–LA reversal, but the reviewer called it RA–LL reversal, the case was considered true. The same method was followed for chest lead reversals. A total of 230 ECGs with an electrode reversal were found in this way. Note that these were not the only ECGs in the database with a true reversal, only those that the algorithm found and were confirmed.

Subsequently, all true positive lead reversals were removed, resulting in 18,424 ECGs, which now did not include any true reversals that were detectable by the algorithm. In order to assess the sensitivity of the algorithm,