Algorithm for Optimal Linear Transformation of 4 Holter Leads for Emphasizing Atypical QRS Complexes

Slavy Mihov[1], Chavdar Levkov[2], Georgy Mihov[3]

Abstract – **Suggested is an algorithm for ECG signal processing for reliable detection and distinguishing of atypical beats in electrocardiograms (ECG). Derived are optimal linear transformations of primary lead signals, which maximize certain criteria for distinction of an atypical beat from the typical ones. These optimal transformations are assumed as new ECG leads, where the atypical beat is enhanced and can be distinguished easily from the typical ones. Two varieties of the method with different optimization criteria are verified experimentally with 4-channel ECG data base of 42 records.**

Keywords – **linear transformation, atypical QRS complex**

I. Introduction

Reliable detection of atypical beats in electrocardiograms (ECG) has been a major task in automated electrocardiography for the last 40 years. Numerous publications concerning this task can be found [1, 2, 3, 4]. At the moment, there are quite reliable algorithms for detection, based on different principles and methods, most of which are heuristic. The shape (pattern) of the QRS complex of an atypical beat in ECG is different from the shape of the typical one. Due to this feature, it is possible to distinguish the two beats. The main issue with the algorithms for automatic recognition is that they must be almost 100% reliable, since rare cardiac disturbances can lead to important diagnostic conclusions. The methods for cardiac diagnosis will benefit very much if recognition reliability reaches close to 100%.

II. Transformation

The surface ECG has spatial origin. A suitable model for this activity is a current dipole source changing its moment, according the different cycles of excitation of myocardium. As a consequence of this model, new leads with desired features can be obtained by linear transformations [5, 6, 7].

Linear transformation forms a new signal V from the signals of four holter ECG leads, according equation:

$$V = a_1 L_1 + a_2 L_2 + a_3 L_3 + a_4 L_4 \qquad (1)$$

[1]Slavy Mihov is with the Faculty of Electronics at Technical University of Sofia, 8 Kl. Ohridski Blvd, Sofia 1000, Bulgaria, e-mail: smihov@tu-sofia.bg.

[2]C. Levkov, is with SIGNACOR Laboratory, 25 Yastrebetz Str., Sofia 1680, Bulgaria, E-mail: info@signacor.com

[3]Georgy S. Mihov is with the Faculty of Electronic Engineering and Technologies of Technical University of Sofia, 8 Kl. Ohridski Blvd, Sofia 1000, Bulgaria, E-mail: gsm@tu-sofia.bg

where L_i are the lead signals and a_i are transformation coefficient for each lead i = 1, 2, 3, 4 [8].

III. Algorithm with Full Combination Set

The conventional linear processing algorithm consists of:

1. The bounds (zones) of chosen typical and atypical QRS complexes are marked manually at the four-lead signals. They are denoted as b_{typ}, e_{typ} and b_{atyp}, e_{atyp}, respectively.
2. Linear transformation of the so marked zones is applied and a set of new signals V_v are obtained according Eq. 1. In the calculations, each of the coefficients $a_{1,v}$, $a_{2,v}$, $a_{3,v}$ and $a_{4,v}$ takes the integer values within the interval [$-q$; $+q$]. Calculating V_v is done for a full combination of the coefficients a_i, which results in $(2q+1)^4$ values for p and respectively – for V_v and $a_{i,v}$. In [9] is shown, that sign change for all coefficients produces the same result, i.e. the images form coefficients [$a_{1,v}$, $a_{2,v}$, $a_{3,v}$ $a_{4,v}$] and [$-a_{1,v}$, $-a_{2,v}$, $-a_{3,v}$ $-a_{4,v}$] are the same but symmetrical. Taking into account only half of all value combinations ,allows reducing the total number of iterations in half, i.e. $(q+1)(2q+1)^3$, which reduces the normalized diapason of just one of the coefficients to [–1; 0].
3. The value of criterion D_v is calculated for all signals V_v
4. The coefficients $a_{i,v}$ of the signal V_v with maximal value of criterion D_v, are used as coefficients of the new signal.
5. The obtained coefficients are normalized according:

$$a_i = \frac{a_{i,p}}{\sqrt{a_{1,p}^2 + a_{2,p}^2 + a_{3,p}^2 + a_{4,p}^2}} \qquad (2)$$

6. The new signal is calculated according equation (1), using the normalized coefficients a_i, for the whole epoch of the signals from the four leads.

IV. Criteria

A. Criterion 1: Ratio of Areas

The criterion based on the ratio of the area of the atypical to the area of the typical QRS complexes is given with:

$$D = \frac{A_{atyp}}{A_{typ}} \qquad (3)$$

where $A_{atyp} = \sum_{v=b_{atyp}}^{e_{atyp}} |V_v|$ is the area of the atypical QRS complex, and $A_{typ} = \sum_{v=btyp}^{etyp} |Vv|$ is the area of the typical complex.

B. Criterion 2: Ratio of Magnitudes

The criterion based on the ratio of the maximal peak-top-peak magnitude of the signal in the atypical QRS complex, to the one of the typical complex is given with:

$$D = \frac{V_{PPatyp}}{V_{PPtyp}} \tag{4}$$

where $V_{PPatyp} = \max(V_v)\Big|_{v=b_{atyp}}^{e_{atyp}} - \min(V_v)\Big|_{v=b_{atyp}}^{e_{atyp}}$ is the difference between the maximal and minimal values of the signal within the zone of the atypical QRS complex and $V_{PPtyp} = \max(V_v)\Big|_{v=b_{typ}}^{e_{typ}} - \min(V_v)\Big|_{v=b_{typ}}^{e_{typ}}$ e is the difference between the maximal and minimal values of the typical complex zone.

C. Criterion 3: Ratio of first derivatives

The criterion based on the ratio of the maximal signal velocity (first derivative) for the atypical QRS complex, to the one for the typical complex is given with:

$$D = \frac{S_{atyp}}{S_{typ}} \tag{5}$$

where $S_{atyp} = \max(|V_v - V_{v+n}|)\Big|_{b_{v=atyp}}^{e_{atyp}}$ is the maximal absolute difference between two successive signal values within the zone of the atypical QRS complex and $S_{typ} = \max(|V_v - V_{v+n}|)\Big|_{b_{v=typ}}^{e_{typ}}$ is the maximal absolute difference between two successive signal values within the zone of the typical complex. The constant n denotes the number of signal samples within one period of the powerline interference, i.e. the difference $V_v - V_{v+n}$ gives the average velocity of the signal during one period of the powerline frequency, thus cancelling its influence.

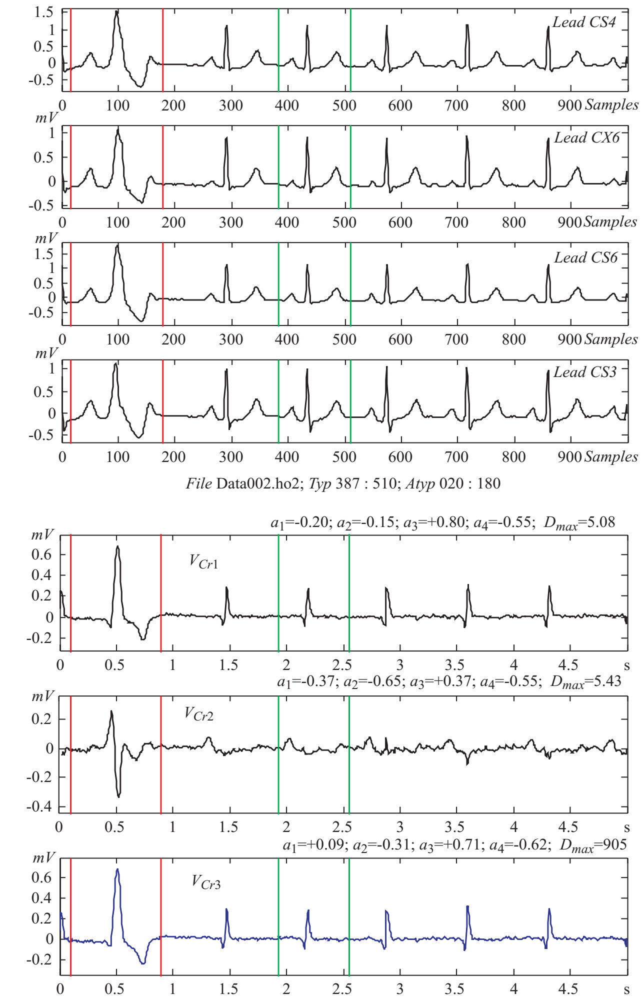

Fig. 1 Results from the three criteria (Data002.ho2)

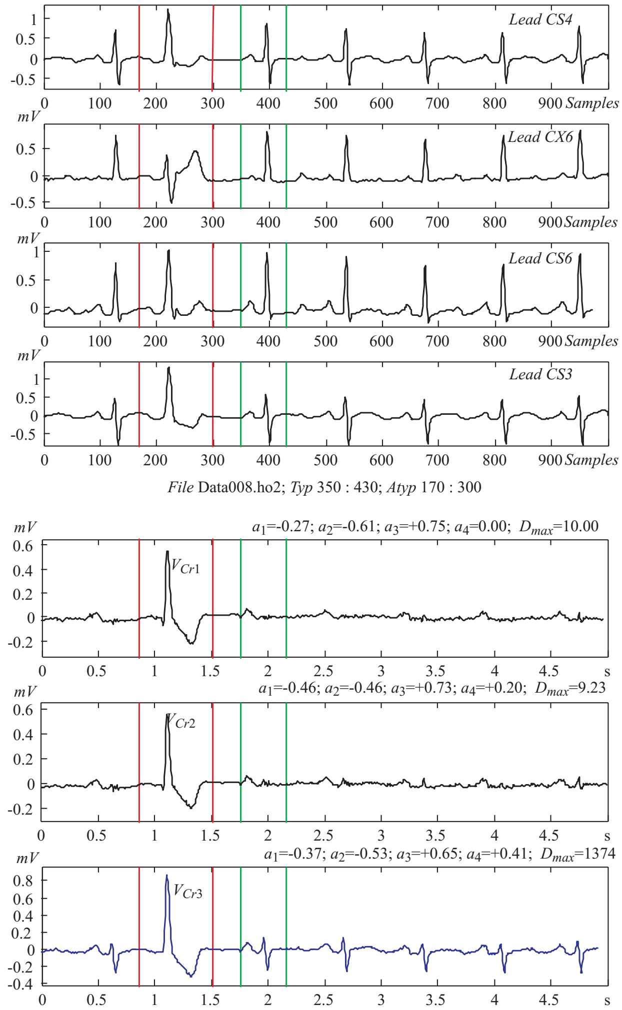

Fig. 2 Results from the three criteria (Data008.ho2)

V. Experiments with the Three criteria

The results from the experiments with 42 pairs of holter leads (SIGNACOR Laboratory database) are shown on the following figures. Each diagram consists: plot of the four holter signal leads being processed; plot of the three resultant signals (obtained by criteria *A*, *B* and *C*, respectively); table with data about the resultant signals from the three criteria (name of the processed record, limits of the typical and atypical beats for that record, estimation coefficients and maximal value of the criterion).

From the experiments made, best visual results are obtained by criterion *B*, as the atypical beats are well emphasized and outstand the rest of the record. Disputable is the best result from record Data033.ho2 (Fig. 1), which can be due to a potentially discredited record (still to be investigated).

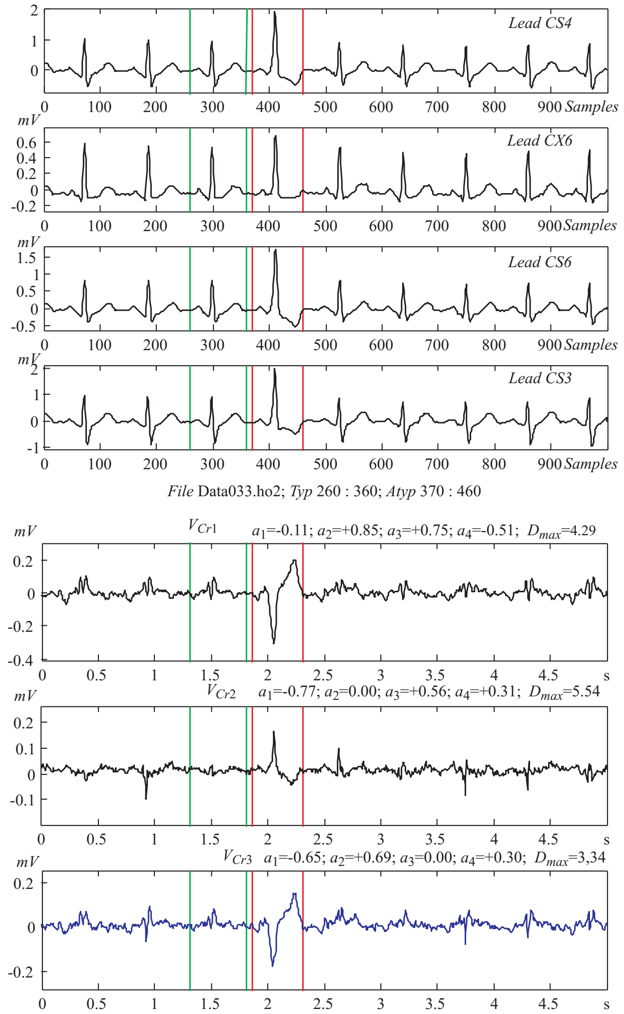

Fig. 3 Results from the three criteria (Data033.ho2)

VI. Algorithm with Full Combination Set in Normalized Scale (Skip Duplicate Combinations)

The algorithm described in section III uses full combination of the coefficients $a_{1,v}$, $a_{2,v}$, $a_{3,v}$ and $a_{4,v}$, taking the integer values within the interval [–*q*; +*q*], to estimate the criterion D_v. The need of obtaining the signal V_v in reasonable range (magnitude comparable with the one of the initial signal leads) requires normalizing the coefficients used according Eq. 2. It appears that the full combination of values for the coefficients $a_{i,v}$ within the interval [–*q*; +*q*], on normalizing generates numerous identical combinations of normalized coefficients a_i within the interval [–1; +1]. For example, the combinations: {8 4 2 0}, {12 6 3 0}, {16 8 4 0} etc. take one and the same form after normalization – {0.87 0.44 0.22 0}. The possible values of the coefficients $a_{i,v}$, which can be used for estimating the criterion D_v are spread evenly within the interval [–*q*; +*q*], but after normalization, different parts of the resultant value interval [–1; +1] become more or less "condensed" and the values can even overlap. Sweeping through the full combination of $a_{i,v}$, when estimating the criterion D_v, corresponds to evaluating multiple times identical or very close combinations of the normalized coefficients a_i. These repetitive computations over the same values do not lead to increasing the precision of the target result, but only waste time. Shortening the computational time can be achieved by eliminating that redundancy of repetitive data.

For this purpose, instead of changing the values of the coefficients $a_{i,v}$ independently from one another, their change is ruled by the equation $a_{1,v}^2 + a_{2,v}^2 + a_{3,v}^2 + a_{4,v}^2 = 1$, which is a direct result from Eq. 2. This significantly reduces the full number of combinations used to estimate the value of D_v. Defined is the so called "normalized scale" of varying the coefficients $a_{i,v}$. It restricts the values of $a_{i,v}$ used in combinations by:

$a_{1,v} \in [-1;+1]$ – discretization interval $1/q$

$a_{2,v} \in \left[-\sqrt{1-a_{1,v}^2};+\sqrt{1-a_{1,v}^2}\right]$ – discretization interval $1/q$

$a_{3,v} \in \left[-\sqrt{1-a_{1,v}^2-a_{2,v}^2};+\sqrt{1-a_{1,v}^2-a_{2,v}^2}\right]$ – discretization interval $1/q$

$$a_{4,v} = \pm\sqrt{1-a_{1,v}^2-a_{2,v}^2-a_{3,v}^2}$$

By this method are used only combinations of coefficients $a_{i,v}$ which values are in normalized relation and thus, processing of duplicate data is avoided. This technique, actually, sweeps through the entire normalized interval with $1/q$ step of discretization. Taking into account that sign change for all coefficients produces the same result (explained in section III), the diapason of the first coefficient $a_{1,v}$ can be reduced to [-1; 0] and thus shrink the computation time in half. The number of iterations for calculating the criterion D_v are roughly $\frac{4}{3}\pi q^3$ (algorithm complexity $O(n^3)$), while the conventional full combination set algorithm has $(q+1)(2q+1)^3$ (algorithm complexity $O(n^4)$).

VII. Experiments with the Algorithm Skipping Duplicate Combinations

Part of the results from the experiments with the proposed algorithm skipping the duplicate coefficient combinations are shown on the figures below. Given are diagrams of the four input signal leads. The fifth diagram is the derived signal with enhanced atypical beat. The database records are processed using optimization criterion *B*, described in section IV. The coefficients $a_{1,v}$, $a_{2,v}$, $a_{3,v}$ and $a_{4,v}$, are evaluated in normalized scale within the interval [–1; +1], with 0.01 discretization step. The obtained results do not diverge noticeably from the reference results, but the computation time is significantly shorter than the conventional algorithm with full combination set.

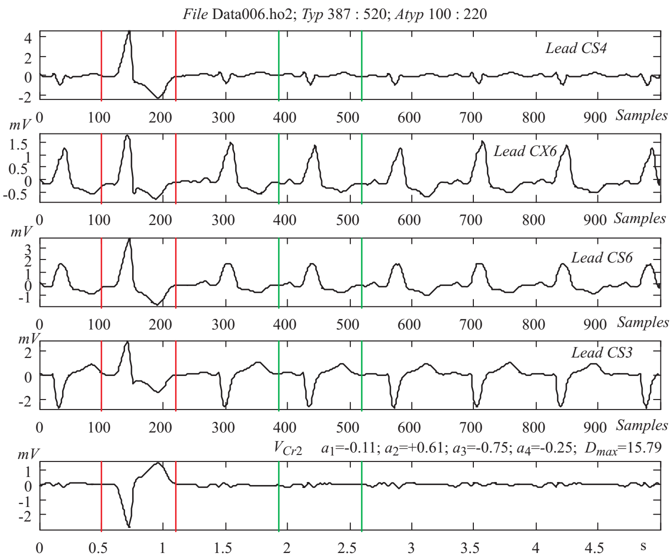

Fig. 4 – Results from Data_006.ho2

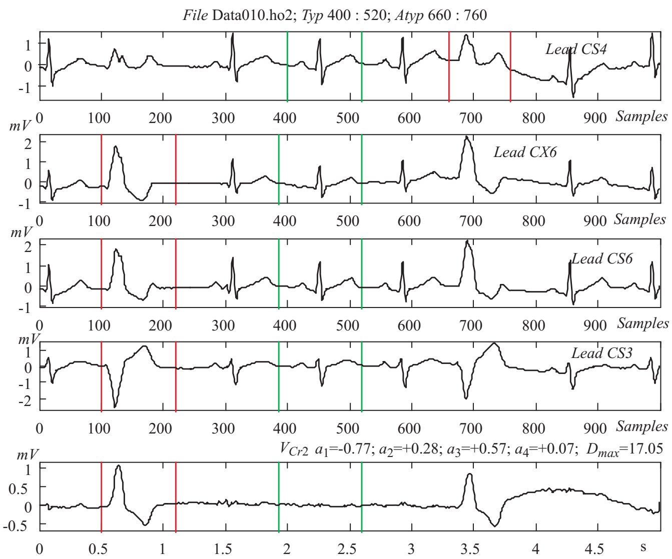

Fig. 5 – Results from Data_010.ho2

VIII. Conclusion

As a general rule, typical and atypical beats have different paths of excitation in the myocardium and hence the representative spatial dipole activity is expected to be different. A logical step is to derive a lead signal which is sensitive to atypical beats and insensitive to the typical ones. In this paper are proposed two variations of a method for linear transformation of four holter ECG leads for enhancing atypical beats. Investigated are three different optimization criteria using a database of 42 4-channel records. The comparison between the results, obtained from the different criteria, gives a subjective estimate for quality. Modification in the algorithm for searching the optimal solution proves to be very efficient in means of computational time, without any sensible reduction of quality. Reducing time in processing four-lead holter records, opens potentials for processing full set of standard 12 ECG lead signals.

The main issue with the algorithms for automatic recognition is that rare cardiac disturbances can lead to important diagnostic conclusions, so they must be almost 100% reliable. Two widely accepted methods for cardiac diagnosis – Bedside ECG monitoring and Holter recording will benefit very much if recognition reliability reaches close to 100%.

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