Algorithm for Optimal Linear Transformation of 12 Standard Leads for Emphasizing Difference between Typical and Atypical QRS Complexes

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Abstract – **An optimal lead is derived by linear transformation of the available primary lead signals, which maximizes certain criteria for distinction of an atypical beat from the typical ones. In this new ECG lead the atypical beats are enhanced and can be distinguished easily from the typical ones. A new fast algorithm for calculation of the optimal transformation is suggested which reduces substantially the number of transformation iterations. The method is compared to the original 'full combination set' method and similar results are obtained. This algorithm reduces drastically the calculation time and now standard 12-leads ECG preprocessing can be performed in reasonable time. Some preliminary results with standard 12-lead preprocesing are given.**

Keywords – **ECG, QRS recognition, linear lead 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. 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. In previous publications [4] a new approach is suggested where the recognition task is made much simpler by multichannel signal preprocesing. A new single lead is derived which is obtained as a linear transformation of the all available primary leads (channels). In this derived signal the atypical beats are enhanced compared to the typical QRS beat. In most of the cases the typical beat almost disappears and the recognition of the atypical beats becomes a trivial task. The new method takes into consideration the spatial relationship between multiple ECG leads where the path of the heart depolarisation is manifested. This important information is ignored in traditional methods for atypical beat recognition.

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 [1, 2, 3].

The linear transformation forms a new signal V from the signals of ECG leads, according equation:

$$V = \sum_{i=1}^{n} a_i L_i \tag{1}$$

where L_i are the lead signals, a_i are transformation coefficient for each lead and n is the number of leads [4].

III. Algorithms for Optimal Linear Transformation

A. Full combination set algorithm

The first used linear processing algorithm consists of the following stages:

1. The beginnings and the ends of the boundaries (zones) of chosen typical and atypical QRS complexes are marked in the original lead signals. They are denoted as b_{typ}, e_{typ} and b_{atyp}, e_{atyp}, respectively.

2. Numerous (v number) linear transformations are calculated and a set of new signals V_v are obtained according Eq. 1. In the process of calculations, each of the coefficients $a_{i,v}$, takes all possible discrete values within a predefined value interval q. The procedure is combinatory. The calculation takes place only in the marked zones.

3. In the marked zones the value of criterion D_v is calculated for all signals V_v.

4. The coefficients $a_{i,v}$ which give maximal value of criterion D_v, are used as coefficients a_i of the optimal transformation.

5. These coefficients a_i are used in Eq. (1) to calculate the new lead signal V for the whole recording where the atypical beat recognition must take place.

Till now, two criteria D (used in the stage 3 of the algorithm) are examined. The first criterion (*Ratio of Areas*) [4, 5] is based on the ratio of the area of the atypical to the area of the typical QRS complexes

$$D = \frac{A_{atyp}}{A_{typ}}, \tag{2}$$

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

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The second criterion (*Ratio of Magnitudes*) [6] is based on the ratio of the maximal peak-to-peak magnitudes of the signals in the atypical and typical QRS complexes

$$D = \frac{V_{PPatyp}}{V_{PPtyp}}, \tag{3}$$

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

The experiments show that both criterion give similar results. The ratio of magnitude criterion is more convenient for use when the zero line of signals is shifted.

B. Normalized combination set algorithm

The procedure for searching the optimal coefficients a_{i} used in the stage 2 of the algorithm is time consuming and must be optimized.

In [4] a procedure is applied with full combination set (simple combinatory). Each of the coefficients $a_{\mathrm{i},v}$ takes all possible integer $2q$ values (step $S = 1/q$) within the interval $[-q; +q]$ which results in $(2q+1)^n$ iteration steps.

It must be noted that simultaneous sign change for all coefficients produces the same result [5]. This allows a reduction of the total number of iterations N in half

$$N = \left(q+1\right)\left(2q+1\right)^{n-1}. \tag{4}$$

The reduction is performed by limitation of the range of one of the coefficients $a \in [-q; 0]$.

Finally all coefficients $a_{\mathrm{i},v}$ are normalized to obtain coefficients a_i of the optimal transformation

$$a_i = \frac{a_{i,v}}{\sqrt{\sum_{i=i}^{n} a_{i,v}^2}}. \tag{5}$$

After the normalization the interval $[-q; +q]$ transforms into $[-1; +1]$ interval.

The full combination set procedure generates numerous linearly dependant (identical in normalized interval) combinations of values for the coefficients $a_{i,v}$. Testing the D criterion for those combinations is redundant and leads to computation overload.

To overcome this disadvantage, in [6] is offered a modified procedure with full combination set performed in normalized scale. Instead of changing the values of the coefficients $a_{i,v}$ independently, their change is ruled by the equation $\sum_{i=i}^{n} a_{i,v}^2 = 1$, which is a direct result from Eq. (5). This significantly reduces the full number of combinations used to estimate the value of D_v. The so called 'normalized scale' of varying the coefficients $a_{i,v}$ is defined. Now there is a restriction of the values of $a_{i,v}$ used in combinations

$$\begin{aligned}
&a_{1,v} \in \left[-1; +1\right], \quad S = 1/q \\
&a_{2,v} \in \left[-\sqrt{\left|1-a_{1,v}^2\right|}; +\sqrt{\left|1-a_{1,v}^2\right|}\right], \quad S = 1/q \\
&\ldots \\
&a_{p,v} \in \left[-\sqrt{\left|1-\sum_{i=1}^{p-1} a_{i,v}^2\right|}; +\sqrt{\left|1-\sum_{i=1}^{p-1} a_{i,v}^2\right|}\right], \quad S = 1/q \,. \\
&\ldots \\
&a_{n,v} = \pm\sqrt{\left|1-\sum_{i=1}^{n-1} a_{i,v}^2\right|}
\end{aligned} \tag{6}$$

Taking into account that the simultaneously sign change for all coefficients produces the same result, the range of the first coefficient $a_{1,v}$ is reduced to [-1; 0].

The number of iterations for calculating the optimal transformations by this algorithm can be roughly express as

$$N \approx \frac{4}{3}\pi q^{n-1}, \tag{7}$$

IV. 12-LEADS EXPERIMENTS WITH NORMALIZED COMBINATION SET

In [4, 5, 6] experiments with linear transformation of four Holter ECG leads [3] were performed. They showed a reliable and stable enhancing of atypical beats.

There are 8 linearly independent signals in the standard 12-leads ECG. For the experiments 8 independent signals are used denoted as R, L, C1, C2, C3, C4, C5 and C6. (all signals are referred to the left leg electrode).

Experiments with 12 selected recordings from standard 12-lead ECG data base were performed. The results of the optimal transformation of one of the recordings are presented on Fig. 1. The procedure with normalized combination set is performed with D criterion *Ratio of Magnitudes*.

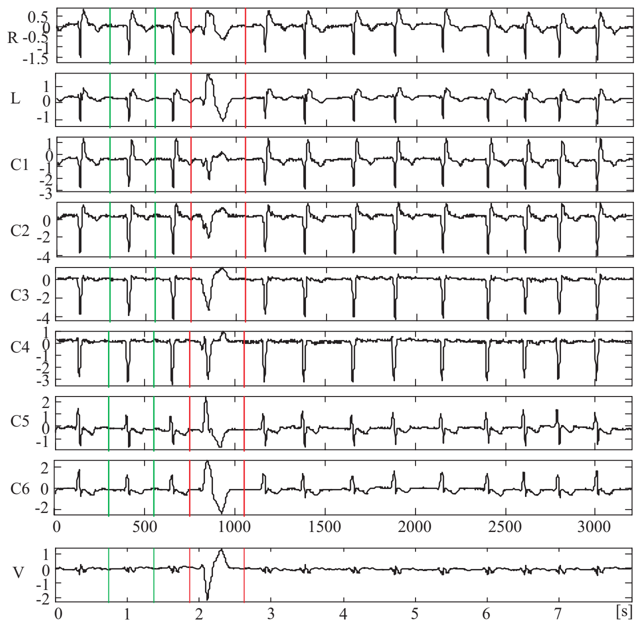
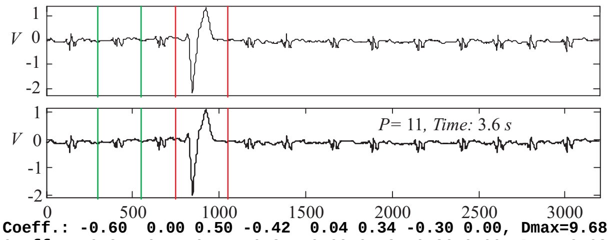
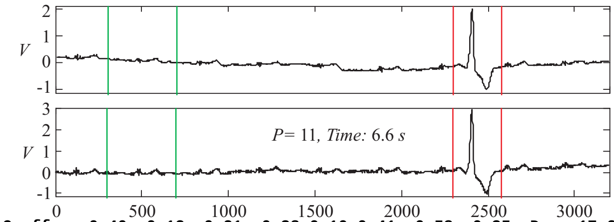


Fig. 1. Result by experiment with normalized combination set.



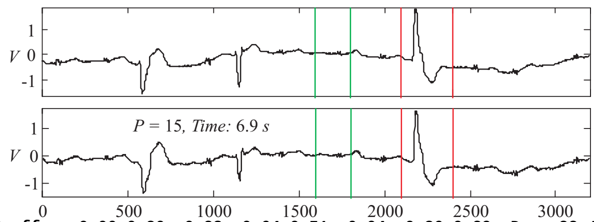
Coeff.: -0.60 0.00 0.50 -0.42 0.04 0.34 -0.30 0.00, Dmax=9.68
Coeff.: -0.31 -0.41 0.55 -0.34 -0.09 0.42 -0.36 0.00, Dmax=9.68

Fig. 2. Recording N0001.adc



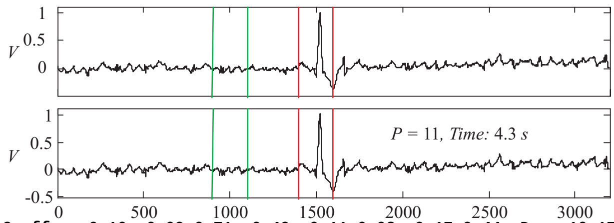
Coeff.: -0.40 -0.12 -0.21 -0.38 0.10 0.41 -0.58 0.35, Dmax=17.20
Coeff.: -0.45 -0.14 -0.07 -0.68 0.05 0.49 -0.12 -0.24, Dmax=15.68

Fig. 3. Recording N0039.adc



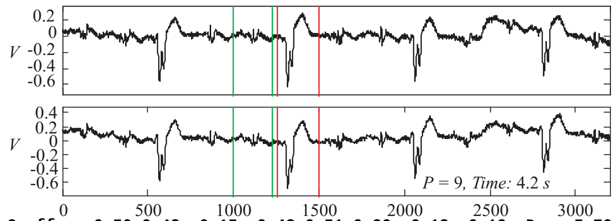
Coeff.: 0.00 0.20 -0.28 -0.64 0.51 0.04 -0.36 0.29, Dmax=22.43
Coeff.: -0.17 0.45 -0.47 -0.47 0.51 -0.17 -0.06 0.17, Dmax=20.19

Fig. 4. Recording N0049.adc



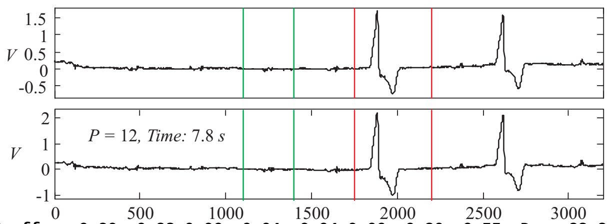
Coeff.: -0.10 -0.09 0.71 -0.49 0.11 0.03 -0.17 0.44, Dmax=10.17
Coeff.: -0.19 -0.08 0.71 -0.37 -0.09 0.24 -0.23 0.44, Dmax= 9.88

Fig. 5. Recording N0056.adc



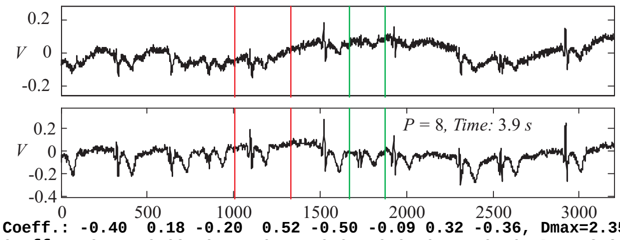
Coeff.: -0.50 0.43 -0.15 -0.43 0.51 0.20 -0.13 -0.19, Dmax=5.70
Coeff.: -0.61 0.41 -0.25 -0.18 0.31 0.07 0.25 -0.45, Dmax=5.65

Fig. 6. Recording N0092.adc



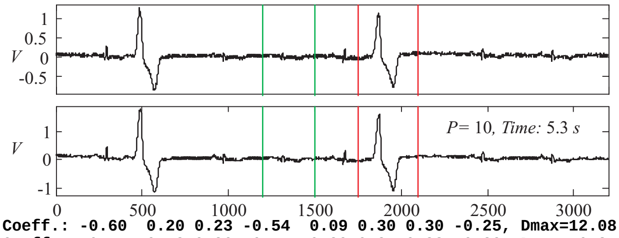
Coeff.: -0.20 -0.28 0.06 -0.04 -0.04 0.66 -0.36 -0.55, Dmax=23.39
Coeff.: -0.31 -0.48 0.19 -0.25 0.28 0.37 -0.28 -0.53, Dmax=21.46

Fig. 7. Recording N0104.adc



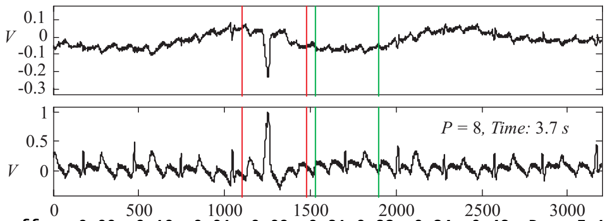
Coeff.: -0.40 0.18 -0.20 0.52 -0.50 -0.09 0.32 -0.36, Dmax=2.35
Coeff.: -0.47 -0.02 0.41 -0.41 -0.05 -0.04 0.44 -0.50, Dmax=2.25

Fig. 8. Recording N0109.adc



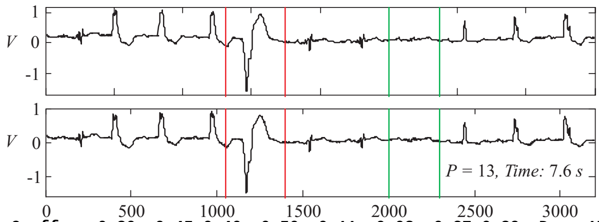
Coeff.: -0.60 0.20 0.23 -0.54 0.09 0.30 0.30 -0.25, Dmax=12.08
Coeff.: -0.51 -0.13 0.26 -0.44 -0.29 0.34 0.33 0.39, Dmax=10.81

Fig. 9. Recording N0113.adc



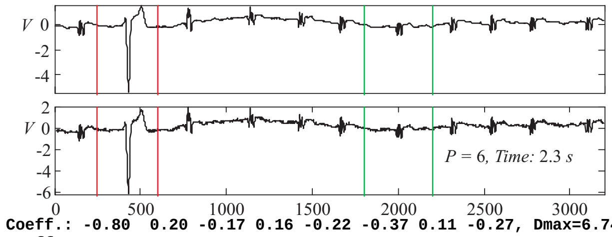
Coeff.: 0.00 0.10 0.01 -0.09 0.21 0.23 -0.84 0.42, Dmax=5.10
Coeff.: -0.01 -0.63 -0.35 0.20 -0.20 0.15 0.48 -0.38, Dmax=3.26

Fig. 10. Recording N0145.adc



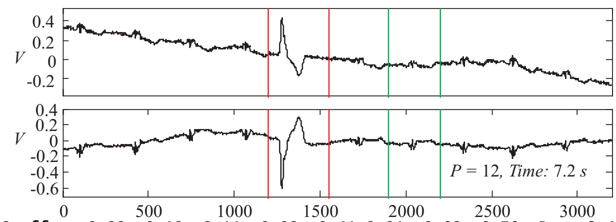
Coeff.: -0.30 -0.45 0.46 -0.50 0.11 -0.08 -0.27 0.39, Dmax=17.68
Coeff.: -0.09 -0.50 0.41 -0.40 -0.03 0.17 -0.52 0.35, Dmax=17.40

Fig. 11. Recording N0211.adc



Coeff.: -0.80 0.20 -0.17 0.16 -0.22 -0.37 0.11 -0.27, Dmax=6.74
Coeff.: -0.13 -0.38 -0.38 0.31 -0.63 -0.13 0.06 -0.44, Dmax=6.53

Fig. 12. Recording N0245.adc



Coeff.: 0.00 -0.10 0.11 -0.09 0.41 0.01 -0.69 0.56, Dmax=8.40
Coeff.: -0.10 0.07 -0.12 -0.13 -0.30 0.10 0.64 -0.67, Dmax=7.41

Fig. 13. Recording N0347.adc

The diagram consists of 8 standard signal leads subplots and a subplot with optimal transformation signal V.

The results show that the method previously applied to 4 Holter leads gives a reliable and stable enhancement of the atypical beat in standard lead case also.

It must be pointed out that even the normalized combination set algorithm takes a substantial computation time (1 hour for 8 signals on 2.8 GHz computer; Matlab implementation).

V. Successive Approximation with Normalized Combination Set

We suggest the following much faster procedure:

1. Each coefficient a is determined in normalized scale according to Eq.6;

2. Starting iteration is performed with step half of the initial interval and the best transformation is determined which gives maximal value of D criterion.

3. In the vicinity of this transformation a new interval for coefficients is defined which is 2 times smaller than the previous interval. The new iteration is performed with 2 times smaller steps. Again the best transformation is determined which gives maximal value of D criterion.

4. Stage 3 is repeated until the best D criterion reaches a value which does not differ from the previous best D with predetermined fixed accuracy value.

The interval in which each coefficient varies is

$$a_{i,r} \in \left[B_{1i};\ E_{1i}\right], \\ B_{1i} = a_{i,r-1} - 1/2^{r}, \quad E_{1i} = a_{i,r-1} + 1/2^{r} \,. \tag{8}$$

Where r is the ongoing number of the passes in the successive approximation ($r = 0, 1, 2, 3, \ldots$). B and E are the beginning and the end of the swept interval respectively.

The normalization scale set requires the coefficient interval to fulfill the Eq. 6

$$a_{i,P} \in \left[B_{2i};\ E_{2i}\right], \\ B_{2i} = -\sqrt{\left|1-\sum_{i=1}^{p-1} a_{i,r-1}^{2}\right|}, \quad E_{2i} = \sqrt{\left|1-\sum_{i=1}^{p-1} a_{i,r-1}^{2}\right|} \,. \tag{9}$$

The actual range of the coefficients fulfilling the above criteria is

$$a_{i,n} \in \left[B_{i};\ E_{i}\right], \quad S = 1/2^{n} \\ B_{i} = \max\left(B_{1i},\ B_{2i}\right), \quad E_{i} = \min\left(E_{1i},\ E_{2i}\right) \,. \tag{10}$$

The number of iterations for calculating the optimal transformations by this algorithm can be roughly express as

$$P \approx N.3^{n} \,. \tag{11}$$

VI. Experiments with Successive Approximation Procedure

The successive approximation procedure is applied to 12 recordings with 8-standard leads. The results of the successive approximation procedure for each recording are compared to corresponding results from normalized combination set procedure. The results of the transformations are presented on Fig. 2 to Fig. 14. On each figure two plots are shown – the upper one is the result from the normalized combination set procedure; the lower one is the result from the successive approximation procedure. Also the corresponding optimal coefficients for both transformations are given in the captions bellow. The number of passes P and the computation time are given in the successive approximation subplot.

VII. Discussions and Conclusions

Typical and atypical beats have different paths of excitation in the myocardium and hence the representative spatial depolarization 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 its original form a ‘brute force’ method was used where the optimal transformation was obtained by calculation of all possible transformations (full combination set) with 4 Holter leads. In this approach all possible transformations must be computed and the calculation time might become impractical even with a powerful computer.

Optimal transformation computed from 12-leads is tested also. The results show that the method previously applied to 4 Holter leads gives also a reliable and stable enhancement of the atypical beats in 8 standard leads. With standard leads the increasing of computation load is significant and faster procedures must be performed obligatory. The new successive approximation procedure reduces the computation time drastically. This modified algorithm proves to be very efficient without any sensible reduction of quality (Fig. 2 – Fig. 13). The substantial reduction in the computation time opens the possibility for processing numerous standard ECG records from large existing data bases in order to test the method for practical clinical applications.

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