

New Approach of Vector ECG Analysis for Revealing Coronary Artery Stenosis

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Introduction

The problem of early recognition of coronary artery (CA) stenosis and lesion location based only on the data from resting electrocardiogram (ECG) is not solved yet at the level that would have practical clinical application value. For these reasons, a point of view of some researchers is that resting ECG data do not contain sufficient information for even potential possibility to reveal CA stenosis [1, 2]. Another group of researchers, applying data mining, artificial intelligence, statistical, and other computer based approaches has been developing methods to reveal CA stenosis at early stages [3].

A multidipole model of the heart for determining CA lesions was developed. The accuracy and value of the multidipole heart model was verified using the coronary angiography results [4]. An approach based on application of singular value decomposition for compact description of P, QRS and T waves was used for detection of CA lesions and their locations [5].

In this paper we proposed a set of 29 geometrical parameters for vector electrocardiogram (VECG) descriptions that were applied to estimate coronary artery stenosis and location of lesion. Such approach is motivated by invariance of such ECG describing parameters on the heart axis. Besides VECG has only three XYZ orthogonal leads that give more integral and stable parameters than the ones derived from the standard 12 lead ECG.

Method

Initial data preprocessing

We used dipolar heart electrical activity model, which state that electrical potentials recorded at any unipolar or bipolar lead can be represented as a linear projection of a time varying three-dimensional electrical vector.

Since at our disposition were digital ECG data with 8 leads: $I, II, V_1, V_2, V_3, V_4, V_5$ and V_6 , we synthesized orthogonal XYZ leads using the following Dower matrix:

$$\begin{bmatrix} 0.156 & 0.010 & -0.172 & -0.074 & 0.122 & 0.231 & 0.239 & 0.194 \\ -0.227 & 0.887 & 0.057 & -0.019 & -0.106 & -0.022 & 0.041 & 0.048 \\ 0.022 & 0.102 & -0.229 & -0.310 & 0.246 & -0.063 & 0.055 & 0.108 \end{bmatrix}$$

The initial 5 min. resting ECG data were recorded with high resolution (FS=2000). To remove ECG trend, digital data were high-pass filtered using first 11 levels of a discrete wavelet transform that correspond to $F_{Low} = FS/2^{11} \approx 1[Hz]$. ECG base line was shifted to zero at the beginning of P wave separately for each lead. After that time series t_n , $n=1,2,\dots,N$, $0 < t_n < 300$ [sec], of outliers of RR intervals for preprocessed vector ECG were estimated by a computer program. Using the t_n sequence the averaged vector ECG was calculated by the following formula:

$$\bar{u}_l(t) = \frac{1}{N} \sum_{n=1}^N u_l(t - t_n), \quad -T/2 < t < T/2.$$

Here $u_1(t) = X(t)$, $u_2(t) = Y(t)$, $u_3(t) = Z(t)$, X, Y and Z are synthetical orthogonal leads of vector ECG, and T denotes the mean value of RR sequence. Averaged on one mean beat-to-beat period X, Y , and Z derivations are not sensitive to measuring distortions and signally reduces amount of ECG data information that is used in identification of coronary artery lesion.

To have more detailed representation of averaged vector ECG and possibility to estimate influence of CA stenosis to different time segments of $X=X(t)$, $Y=Y(t)$, and $Z=Z(t)$ leads, averaged vector ECG was additionally partitioned in time domain. From averaged X, Y , and Z leads three parts corresponding to P, QRS waves and ST interval were chosen. For each averaged ECG these time

segments were extracted by a computer algorithm with possibility to edit extracted time intervals by a trained person.

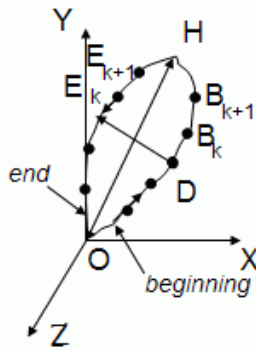


Fig. 1. Geometrical parameters of 3-D loop of a wave of averaged ECG

Each P, QRS wave and ST interval is described by 7 parameters that reflect geometrical properties of three-dimensional curve of vector ECG, which we call 3D loop for simplicity. For quantitative measuring of the parameters we used K points \mathbf{B}_k at the initial part of the 3D loop and the same number of points \mathbf{E}_k at the final part of the one. Locations of \mathbf{B} and \mathbf{E} points were defined by the following the equations:

$$|\mathbf{B}_k| = |\mathbf{E}_k| = H(k + 0.5) / K, \quad k = 0, 1, \dots, K - 1.$$

Table 1. Geometrical parameters for a single (P, QRS, or ST) 3D loop of vector ECG.

Nr	Description
1	<i>A screw characteristic of 3D loop.</i> The parameter is defined as the maximum of spatial angles by which $(\mathbf{E}_{k-1}, \mathbf{E}_k, \mathbf{E}_{k+1})$ and $(\mathbf{B}_{k-1}, \mathbf{B}_k, \mathbf{B}_{k+1})$ points are seeing from \mathbf{E}_{k-2} and \mathbf{B}_{k-2} positions respectively. If 3D loop belongs to a plane, this parameter equals zero.
2	<i>Non regularity of the loop at the end.</i> The parameter is defined as the maximum of spatial angles by which are seeing $(\mathbf{E}_{k-1}, \mathbf{E}_k, \mathbf{E}_{k+1})$ points from \mathbf{B}_k position. If after maximum point \mathbf{H} the loop belongs to a plane, this parameter equals zero.
3	<i>"Spatialness" of the loop.</i> The parameter is defined as the maximum of angles between two adjacent vectors: $\overrightarrow{\mathbf{B}_k \mathbf{E}_k}$ and $\overrightarrow{\mathbf{B}_{k+1} \mathbf{E}_{k+1}}$.
4	<i>Non regularity of the loop at the beginning.</i> The parameter is defined as maximum of spatial angles by which $(\mathbf{B}_{k-1}, \mathbf{B}_k, \mathbf{B}_{k+1})$ points are seeing from \mathbf{E}_k position. If the loop until the maximum \mathbf{H} point belongs to a plane, this parameter equals zero.
5	<i>D – diameter of the loop.</i> The parameter is defined as the maximum of distances between \mathbf{B}_k and \mathbf{E}_k points.
6	<i>H - height of the loop.</i> The parameter is defined as the maximal distance of 3D loop points from the zero point.
7	<i>Thickness of the loop.</i> The parameter is defined as ratio of the <i>diameter</i> and <i>height</i> of the loop.

Here H is height of the loop which is defined as the maximal distance of 3D loop points from the zero point. Fig. 1 illustrates H , \mathbf{B}_k , and \mathbf{E}_k points for the case $K=5$. In our calculations we used $K=17$.

In Table 1 definitions of the 7 geometrical parameters for a single 3D loop are presented. Since we considered 3 different loops that origin from P, QRS waves and ST interval the total number of different geometrical parameters describing a single loop is equal to $21=3 \times 7$. Let us remark that each parameter is invariant under group of rotation of XYZ axes. Since the Dower matrix is constructed under assumption that derived XYZ leads would be orthogonal, one can state that parameters under consideration are non-sensitive to the heart axis. All parameters, except *diameter* and *height*, are invariant under dilatation that provides an additional data dimensionality reduction which is important for robustness of statistical and artificial neural networks based classification and recognition methods.

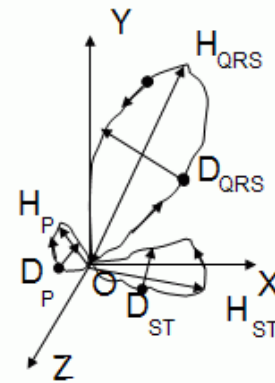


Fig.2. Vectors that are used in description of relation of 3-D loops corresponding to P, QRS wave and ST interval of averaged ECG.

Table 2. Geometrical parameters reflecting relation of P, QRS, and ST 3D loops and used in recognition of coronary artery stenosis and localization.

Nr	Description
1	Angle between \mathbf{H}_{QRS} and \mathbf{H}_{ST} vectors.
2	Angle between \mathbf{H}_{ST} and \mathbf{H}_P vectors.
3	Angle between \mathbf{H}_P and \mathbf{H}_{QRS} vectors.
4	Spatial angle formed by \mathbf{H}_{QRS} , \mathbf{H}_{ST} , and \mathbf{H}_P vectors.
5	Spatial angle formed by \mathbf{H}_{QRS} , \mathbf{D}_{QRS} , and \mathbf{H}_{ST} vectors.
6	Spatial angle formed by \mathbf{H}_{ST} , \mathbf{D}_{ST} , and \mathbf{H}_P vectors.
7	Spatial angle formed by \mathbf{H}_P , \mathbf{D}_P , and \mathbf{H}_{QRS} vectors.
8	Spatial angle formed by \mathbf{D}_{QRS} , \mathbf{D}_{ST} , and \mathbf{D}_P vectors.

In Table 2 are presented 8 additional geometrical parameters that describe interrelation of three 3D loops corresponding to P, QRS wave and ST interval. Fig 2 illustrates meaning of vectors \mathbf{H}_P , \mathbf{H}_{QRS} , \mathbf{H}_{ST} , \mathbf{D}_P , \mathbf{D}_{QRS} , and \mathbf{D}_{ST} that were used in the definitions. All defined in Table 2 parameters are invariant under 3-parameter rotation and 1-parameter dilatation group. Thus they are independent on the heart axis that supports they use as robust descriptors of averaged vector ECG.

Summarizing one can state that total number of geometrical parameters used in description of averaged vector ECG is equal to 29 ($7 \times 3 + 8$). All these parameters are independent on the heart axis and 23 of them do not depend on ECG dilatation.

Patients and classification method

195 patients with stable and unstable angina pectoris were investigated (138 men and 57 women). To evaluate CA stenosis, for all the patients coronary angiography was performed.

By recommendation of American Heart Association, coronary arteries are divided into segments: right coronary artery (RCA) – 1, 2, 3, 4 segments; left main – 5 segment, left anterior descending artery (LAD) – 6, 7, 8, 9, 10 segments and circumflex artery (CXA) – 11, 12, 13, 14, 15 segments. 1, 5, 6 and 11 segments are proximal; 2, 7, 12, 13 – middle; 3, 4, 8, 9, 10, 14, and 15 – distal. The degree of stenosis in each segment was scored from 0 to 4 points (0, $0 \leq 25\%$; 1, $26-50\%$; 2, $51-75\%$; 3, $76-90\%$; 4, $>90\%$ stenosis), and the extent score of coronary stenosis was defined as the sum of scores of all segments [6].

According to the sum of scores of all segments, the patients were divided into two main groups: the first (I) group consists of patients having the sum of scores of all segments < 2 and the second group of the ones having the sum of scores of all segments ≥ 2 . According to the numbers of stenotic vessels the second (II) group was divided into three subgroups: IIa – one vessel disease, IIb – two vessel disease, and IIc – three vessel disease.

The first patient group (age 56.4 ± 10.2) consisted of 45 men and 27 women. The second patient group (age 60.8 ± 9.5) consisted of 93 men and 30 women. One vessel disease was diagnosed in 52 patients, two vessel disease – in 32 and three vessel disease – in 44 patients. LDA segment narrowing was determined in 109 patients; CXA – in 62 and RCA – in 53 patients.

For discrimination of I and II groups, we used logistic regression [7]. At first stage for each single geometrical parameter logistic regression was performed and parameters with $p < 0.05$ were included into the subset of 29 geometrical parameters that later were used for multiple logistic regression. Identical classification was performed for IIa, IIb, and IIc groups.

Results

Sensitivity and specificity of the classification for prediction CA stenosis were estimated using ROC curves (Fig. 3).

The curve was obtained by application of multiple logistic regression method, the area under the curve was 0.74. The correlation coefficient of the correct recognition equals 0.317.

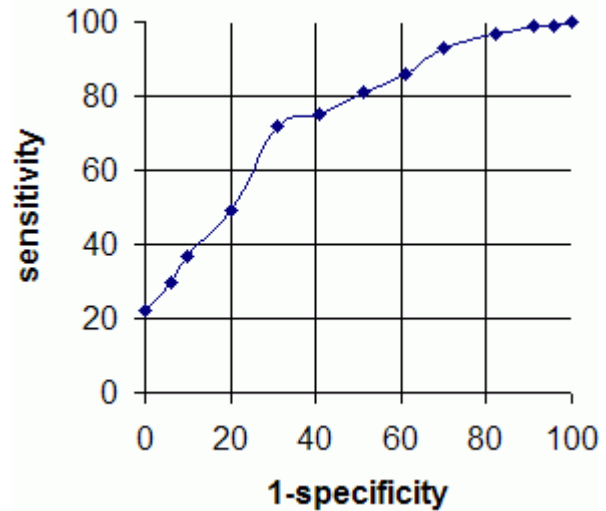


Fig. 3. ROC curve of classification of I and II groups

For method verification the testing set of 55 ECGs were used. The set consisted of 24 patients, who belongs to the first group and 31 patients, who belongs to the second. Patients of the test set with earlier defined classification parameters were discriminated with 67% sensitivity and 67% specificity; the correlation coefficient of the correct classification was equal to 0.33. Thus classification quality was slightly better for the test data than the one for the training set. Comparing with classification based on ECG data [8], one can state that both classifications on the training set give comparable results ($r=0.32$ and 0.34 respectively). However vector ECG based classification ($r=0.33$) outperformed than ECG based classification ($r=0.05$) on the test set.

Vector ECG and multiple logistic regression based classification of RCA lesion was performed with $r=0.35$ for the training set and $r=0.37$ for test set, area under ROC curve equals 77%. LDA and CXA were classified with $r=0.33$ and 0.32 and with area under ROC curve 72% and 75% respectively.

Conclusions

1. A set of 29 geometrical parameters for analysis of VECG and descriptions that were applied to estimate coronary artery stenosis and their location was proposed in this paper.

2. X, Y, Z orthogonal leads give more integral and stable parameters than the ones derived from the standard 12 lead ECG. This can be more precisely applied for the preliminary recognition of coronary artery lesions.

3. Coronary artery stenosis identification based on multiple logistic regression method and VECG descriptors outperformed better than one based on ECG descriptors.

Note: Work of this author was partially supported by Lithuanian State Science and Studies Foundation, Grant No. C-07/2003.

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Pateikta spaudai 2004 02 28

A. Bastys, J. Blužas, S. Kaminskiene, R. Navickas, G. Urbonavičienė. Vainikinių arterijų susiaurėjimų nustatymas taikant vektorokardiografinius parametrus // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2004. – Nr. 2(51). –P. 82-85.

Pateikiama širdies vainikinių arterijų stenozės ir širdies išemijos vektorinės elektrokardiogramos parametrais besiremianti kompiuterinė prognozė. Širdies ciklo laiko intervale vidurkinta vektorinė elektrokardiograma aprašoma 29 nepriklausančiais nuo širdies ašies geometriniais parametrais. Klasifikavimas remiasi daugiamatės logistinės regresijos metodu. Klasifikacijos parametrus rasti panaudota 195 pacientų apmokymo imtis, klasifikavimo kokybės tikrinimui naudojama 55 pacientų testinė imtis. Palyginami klasifikavimo rezultatai naudojant vektorinės ir įprastos elektrokardiogramos parametrus. Pasiūlytai metodikai, skirtingai nuo tų pačių autorių anksčiau taikytos metodikos, nepastebėta persimokymo efekto. . Il. 3, bibl. 8 (anglų kalba; santraukos lietuvių, anglų ir rusų k.).

A. Bastys, J. Blužas, S. Kaminskiene, R. Navickas, G. Urbonavičienė. New Approach of Vector ECG Analysis for Revealing Coronary Artery Stenosis // Electronics and Electrical Engineering. – Kaunas: Technologija, 2004. – No. 2(51). –P. 82-85.

A vector ECG parameters based computer prognosis of coronary artery stenosis and ischaemic heart diseases is proposed. Averaged vector ECG is described by 29 geometrical parameters that are independent on the heart axis. Classification is made by multiple logistic regression method. Classification parameters are defined by a training set of 195 patients; classification is verified on test set containing 55 patients. Classification results performed using vector ECG and 12 lead ECG parameters were compared. As distinct from earlier authors, new method didn't mark overtraining problem. Ill. 3, bibl. 8 (in English; summaries in Lithuanian, English and Russian).

Бастис А., Блуžas Й., Каминскене С., Навицкас Р., Урбонавичене Г. Новый подход к анализу векторкардиограммы для определения поражений коронарных артерий // Электроника и электротехника. - Каунас: Технология, 2004. — № 2(51). –С. 82-85.

Описываются результаты определения корреляции между параметрами векторкардиограммы и степенью поражения коронарных артерий. Усредненная векторкардиограмма описывается 29 геометрическими, независимыми от положения оси сердца, параметрами. Классификация проведена при помощи логической регрессии. Для определения информативных параметров классификации была использована выборка из 195 больных. Качество классификации проверялось на тестовой выборке состоящей из 55 больных. Предложенная новая методика не страдает от эффекта излишней адаптации к данным выборки обучения, чем положительно отличается от ранее применяемой методики тех же авторов. Ил. 3, библи. 8 (на английском языке; рефераты на литовском, английском и русском яз.).

DOI: 10.5755/j02.eie.10968