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METHOD OF AUTOMATIC DETERMINATION OF THE HEART'S ELECTRICAL AXIS IN CARDIOLOGICAL DECISION SUPPORT SYSTEMS

Anna E. Filatova[1)]
ORCID: http://orcid.org/0000-0003-1982-2322; filatova@khpi.edu.ua
Mohamad Fahs[1)]
ORCID: http://orcid.org/0000-0001-7776-3311; fahes_93mohamad@hotmail.com
[1)] National Technical University "Kharkiv Polytechnic Institute", 2, Kyrpychova Str., Kharkiv, Ukraine

ABSTRACT

The work is devoted to solving the scientific and practical problem of automating the heart's electrical axis calculation to improve the quality of morphological analysis of biomedical signals with locally concentrated features in cardiological decision support systems, which in turn reduces the likelihood of medical errors. The work shows that existing methods for in the determining the electrical axis of the heart require morphological analysis of an electrocardiogram. The method is based on determining the integral signal in the frontal plane from all limb leads, taking into account the lead angle in the hexaxial reference system. In graphic form in polar coordinates, the integral electrocardiological signal is a figure, predominantly elongated along the axis, the direction'n of which corresponds to the heart's electrical axis. The position of the heart's electrical axis is calculated as the angle between the axis of standard lead I and the vector, the end of which is at the center of mass of the locus of the points the farthest away from the reference point. Cluster analysis is used to find the most distant points from the reference point. The proposed method for of calculating the heart's electrical axis makes it possible not to carry out a preliminary morphological analysis of an electrocardiogram. To implement the method proposed in the article, a program was written in the Matlab language, which is connected as a dynamic link library to the cardiological decision support system "TREDEX telephone" operating as part of the medical diagnostic complex "TREDEX" manufactured by "Company TREDEX" LLC, Kharkiv. Verification of the results was carried out using a database of electrocardiograms, which were recorded using a transtelephone digital 12-channel electrocardiological complex "Telecard", which is part of the medical diagnostic complex "TREDEX", and deciphered by cardiologists of the communal non-profit enterprise of the Kharkiv Regional Council "Center for Emergency Medical aid and disaster medicine". Comparison of the results of calculating the heart's electrical axis according to electrocardiograms by a doctor and automatically using the proposed method showed that in the overwhelming majority of cases the decisions made coincide. At the same time, cardiologists make mistakes, and errors are made during automatic calculation using the proposed method. The paper explains the reasons for these errors.

Keywords: Morphological analysis; biomedical signal; locally concentrated features; cardiological decision support system; electrocardiogram; heart's electrical axis; integral electrocardiological signal; hexaxial reference system

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INTRODUCTION

Telemedicine has become widespread in connection with the health care system reform in Ukraine. The main goal of telemedicine is to provide highly qualified medical care not only to residents of large cities in which there is a developed network of medical institutions but also to residents of remote settlements by organizing access to the best regional doctors.

In the pilot project "Telemedicine" which was launched in 2019 as part of the medical reform of Ukraine, there is planned to provide medical services in four nosologies:
- cardiovascular;
- endocrinological;
- respiratory diseases;
- dermatological.

Thus, cardiology is one of the effective areas of telemedicine application. At the same time, in order to introduce telemedicine into cardiology, it is necessary to develop new and improve existing medical diagnostic systems which include the cardiological decision support systems (DSS) in addition to specialized equipment. One of such diagnostic complexes is the medical diagnostic complex "TREDEX" (manufactured by "Company TREDEX" LLC, Kharkiv) which includes the cardiological decision support systems "TREDEX telephone" [1].

LITERATURE REVIEW

The most common way to diagnose the heart and cardiovascular system conditions is morphological analysis of an electrocardiogram (ECG) [2-3] with the following analysis of the amplitude-time parameters [4-5], as well as the shape of waves and complexes which are found [6-7]. In this case, an ECG is a biomedical signal (BMS) with locally concentrated features (LCF).

BMS with LCF are biomedical signals with a structure in which diagnostic features are concentrated on small fragments of their definition area. These fragments are called structural elements. The task of the morphological analysis is to isolate informative fragments (structural elements) of BMS with LCF against the background of noise [8-9].

The ECG interpretation algorithm consists of the following steps [10-11]:

1) Determination of the heart rhythm. The heart rhythm is determined by comparing the duration of cardiac cycles (the distance between the tops of the R–R waves).

2) Determining the source of the pacemaker. The source of the pacemaker is determined based on the assessment of the excitation course along the atria and ventricles, i.e. based on analysis of the amplitude, duration, polarity and shape of the P wave. There is sinus, atrioventricular and ventricular rhythms.

3) An ECG voltage is determined by the sum of the absolute values of the QRS complex in each of the standard leads.

4) Determination of heart rate (HR) based on the duration of R–R intervals.

5) Determination of the position of the heart's electrical axis.

The heart's electrical axis (QRS axis) is the projection direction of the resulting electrical vector of ventricular excitation (reflects the QRS complex of an ECG) relative to the axis of standard lead I to the frontal plane which is expressed by the angle α between the axis itself and the positive (right) half of the axis of standard lead I, located horizontally [12- 13]. The angle α is considered positive if it is below the horizontal line, and negative if the angle is above it.

There are many ways to calculate the position of the QRS axis [14-15], but at the first stage, the waves amplitudes of the QRS complex are always assessed in six standard leads (I, II, III, aVR, aVL, aVF) which make up the frontal plane and the hexaxial reference system (Fig. 1).

There are the following options for the location of the heart's electrical axis [16]:

– the normal QRS axis (from $+30°$ to $+69°$);
– left axis deviation, LAD (from $-90°$ to $0°$);
– horizontal axis deviation (from $0°$ to $+29°$, intermediate between normal position and LAD);
– right axis deviation, RAD (from $+91°$ to $+180°$);
– vertical axis deviation (from $+70°$ to $+90°$, intermediate between normal position and RAD);
– an extreme or an indeterminate axis (from $-180°$ to $-90°$).

It should be noted that sometimes cardiologists distinguish the semi-horizontal and semi-vertical position of the heart's electrical axis. At the same time, in the foreign literature, the position of the heart's electrical axis in the range from $-30°$ to $+90°$ is considered normal [6].

6) Analysis of waves (amplitude, duration, polarity, shape) and intervals (duration, for segments – deviation from the isoline, shape and magnitude of the shift).

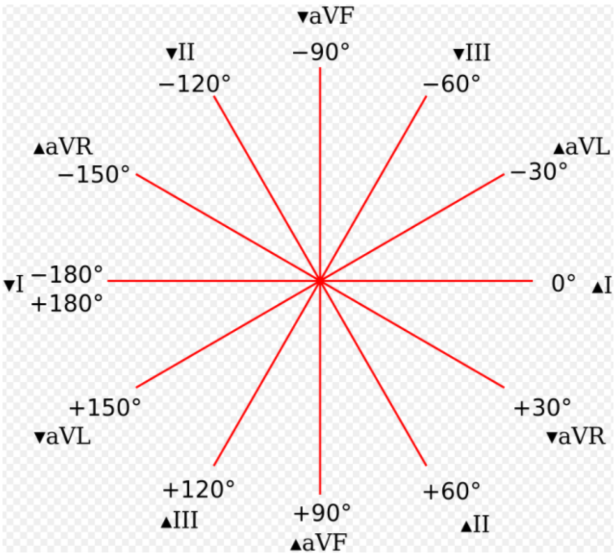

Fig. 1. **The hexaxial reference system**
Source: **https://en.wikipedia.org/wiki/Hexaxial_reference_system**

It should be noted that determining the position of the heart's electrical axis is one of the key steps in the interpretation of an ECG. The ability to determine the heart's electrical axis can provide insight into the basic conditions of the disease and help identify a variety of possible diagnoses [17-18]. For example, often left bundle branch block or left ventricular hypertrophy is accompanied by a deviation of the QRS axis to the left [19-20], and left ventricular hypertrophy or lateral ventricular infarction is accompanied by a deviation of the QRS axis to the right [21-22].

From the above ECG interpretation algorithm, it is easy to see that none of the above items can be performed without the morphological analysis of an ECG.

In [23], the authors proposed the method for morphological analysis of BMS with LCF based on matched morphological (MM) filtration. The main idea of the method is as follows.

The authors determined the morphological similarity coefficient (MS coefficient) of patterns $a \in \Omega$ and $b \in \Omega$ by the shape matched with the model M:

$$K_{MS}(a,b,\mathrm{M}) = K\left(\Pr(a,\mathrm{M}),\Pr(b,\mathrm{M})\right), \quad (1)$$

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where: $K(\cdot)$ is a potential function reflecting the closeness of patterns *a* and *b* by the shape matched with the model M; $\Pr(a,\mathrm{M})$, $\Pr(b,\mathrm{M})$ are the operations of projecting the patterns *a* and *b* onto the model M respectively.

The morphological similarity coefficient (1), calculated for a signal fragment in a given window *w*, is called the local morphological similarity coefficient $K_{MS}^{w}(a,b,\mathrm{M})$.

The detection function $\tilde{y}[t]$ is calculated and analyzed to localize the sought structural elements (i.e. waves and complexes of an ECG). The values of the detection function are determined using the local morphological similarity coefficient K_{MS}^{w} of the form (1):

$$\tilde{y}[t] = K_{MS}^{w[t]}\left(\omega_p, \omega_t, \mathrm{M}_p\right),$$

where: ω_p is standard of structural elements of the target class; ω_t is signal projection within filter aperture on the shape matched with useful one-dimensional signal model M_p of the sought structural element.

Based on the analysis of the detection function $\tilde{y}[t]$, the local morphological matching (MM) coefficient $K_{MM}^{w[t]}$ is calculated using the threshold decision rule:

$$K_{MM}^{w[t]}\left(\omega_p, \omega_t, \mathrm{M}_p\right) = \begin{cases} 1 \ \ \forall t \in [t_{0j}; t_{0j} + T_0] & \text{if } \tilde{y}[t_{0j}] > Pd[t]; \\ 0 & \text{in other cases} \end{cases} \quad (2)$$

where: $Pd[t]$ is an adaptive threshold; t_{0j} is a local maximum point of function $\tilde{y}[t]$ such that $\tilde{y}[t_{0j}] \geq \tilde{y}[t] \ \ \forall t \in \dot{\mathbf{M}}(t_{0j})$; $\dot{\mathbf{M}}(t_{0j}) = \mathbf{M}(t_{0j}) \setminus \{t_{0j}\}$ is punctured neighborhood of a point t_{0j}; $\mathbf{M}(t_{0j})$ is a neighborhood of a point t_{0j}; *j* is an index of a local maximum.

The authors proposed several methods for calculating the adaptive threshold $Pd[t]$ of the decision rule (2).

The simplest one is that the value $Pd[t] = const$ and is determined as a result of a learning or self-learning procedure [24].

In the absence of a training sample, the definition of the adaptive threshold $Pd[t]$ is based on the use of the idea of cluster analysis [25].

Another way of determining $Pd[t]$ in the absence of a training sample is based on the use of the algorithm for calculating adaptive threshold values, which is used to isolate QRS complexes in real-time ECG systems [26].

MM-filter response is calculated like this:

$$\tilde{x}[t] = x^0 + K_{MM}^{w[t]}(\omega_p, \omega_t, \mathrm{M}_p)(x[t] - x^0), \quad (3)$$

where: $x[t]$ is input BMS with LCF; $x^0 = const$ is constant determining signal level which corresponds to the absence of assigned type structural element in current fragment of signal (for instance, ECG baseline level).

Thus, to implement the method, it is necessary to set the standard ω_p of the required class of structural elements.

The parameters of the standard, first of all, depend on the position of the heart's electrical axis. This is due to the following circumstances [27]. If the average electric vector of the heart (or the QRS axis) moves to the positive electrode then a positive complex is recorded on the corresponding lead, and if it moves away from the positive electrode – a negative one (Fig. 2).

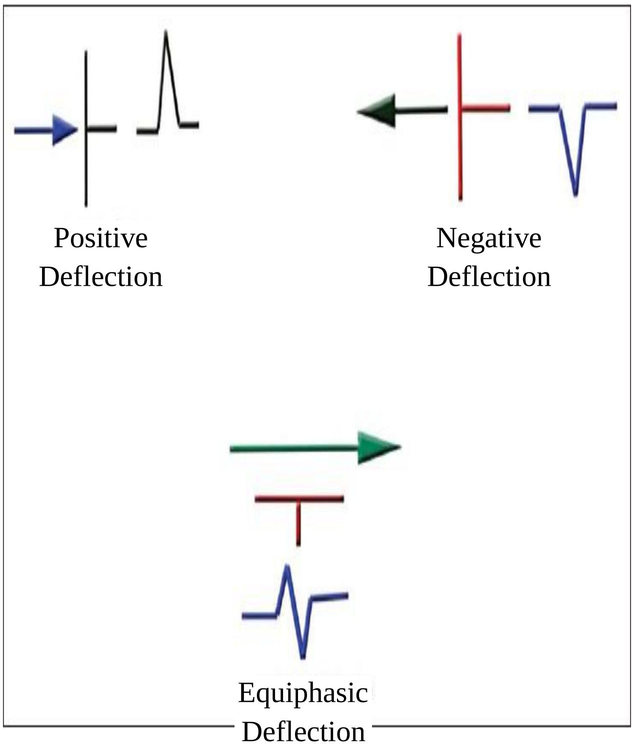

Fig. 2. **QRS complex formation scheme**
Source: **[27]**

If the QRS axis is perpendicular to the positive electrode then an equiphasic and/or isoelectric complex is recorded on the corresponding lead (Fig. 2).

Based on the above, we can conclude that in order to search for the heart's electrical axis, it is necessary to perform morphological analysis of ECGs, which, in turn, requires knowledge of the heart's electrical axis for the correct setting of the standard ω_p of QRS complexes.

Thus, the automatic search for the heart's electrical axis without preliminary morphological analysis of an ECG is an urgent scientific and practical task.

The purpose of the study is to automate the calculation of the heart's electrical axis to improve the quality of morphological analysis of ECGs in cardiological decision support systems, which in turn reduces the likelihood of medical mistakes.

To achieve this goal, the following tasks are solved:

– to develop a method for automatic determination of the heart's electrical axis without the need to search and analyze QRS complexes;

– to develop software for the module of automatic determination of the heart's electrical axis for cardiological decision support system;

– to perform verification of the developed method with real electrocardiograms.

METHOD OF AUTOMATIC DETERMINATION OF THE HEART'S ELECTRICAL AXIS

The simplest method for determining the position of the heart's electrical axis is the quadrant method [28-29]. For this, the amplitudes of the QRS complex are analyzed only in leads I and aVF. In this case, the following rules are used (Fig. 1):

– if the QRS complex is positive in leads I and aVF then the QRS axis is normal;

– if the QRS complex is positive in lead I, and is negative in lead aVF then the QRS axis is deviated to the left;

– if the QRS complex is negative in lead I, and is positive in lead aVF then the QRS axis is deviated to the right;

– if the QRS complex is negative in leads I and aVF then the QRS axis is extremely deviated or undetermined.

This method allows only estimating the direction of the heart's electrical axis without calculating the angle α. In addition, the quadrant method does not allow determining the position of the heart's electrical axis in cases where lead I or aVF is isoelectric.

A more accurate method for determining the position of the heart's electrical axis is the three-lead method [28] in which there are analyses of the QRS complex amplitudes in leads I, II and aVF (or III). In this case, the following rules are used (Fig. 1):

– if the QRS complex is positive in leads I, II and aVF (or III) then the QRS axis is normal;

– if the QRS complex is positive in lead I, equiphasic in lead II, and negative in lead aVF (or III) then the QRS axis is deviated to the left (from $-30°$ to $0°$);

– if the QRS complex is positive in lead I, and negative in leads II and aVF (or III) then the QRS axis is deviated to the left (from $-90°$ to $-30°$);

– if the QRS complex is negative in lead I, and positive in leads II and aVF (or III) then the QRS axis is deviated to the right;

– if the QRS complex is negative in leads I, II and aVF (or III) then the QRS axis is extremely deviated;

– if the QRS complex is equiphasic in leads I, II and aVF (or III) then the QRS axis is undetermined.

Another method for determining the position of the heart's electrical axis is based on determining the most isoelectric lead in the frontal plane [28].

The method consists of the following steps:

1) Determine the most isoelectric lead, i.e. a lead in which is a biphasic QRS complex (the amplitude of the R wave is approximately equal to the amplitude of the Q or S wave) or a smoothed QRS complex (no noticeable changes).

2) Determine the lead with the tallest R-waves (or with the largest R/S ratio).

3) The heart's electrical axis is perpendicular to the isoelectric lead and is directed towards the most positive lead.

There are also methods that allow specifying the direction in case none of the standard leads is isoelectric [30].

If the difference between the amplitudes of the R and S waves in the isoelectric lead is 0-1 mm then correction of the angle α is not required.

If the difference between the amplitudes of the R and S waves is 2-3 mm in the isoelectric lead then the angle α is corrected by $10°$ towards the positive or negative pole of the smallest QRS complex.

If the difference between the amplitudes of the R and S waves is 4-5 mm, then the angle α is corrected by $15°$ towards the positive or negative pole of the smallest QRS complex.

The position of the heart's electrical axis can also be calculated using a combination of two leads, for example, according to the following expressions [31-32]:

$$\alpha = \pm arctg \frac{V_{III}}{V_I} ,$$

or

$$\alpha = \pm arctg \frac{2V_{aVF}}{\sqrt{3}V_I} ,$$

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where V_{III}, V_{aVF}, V_I are the algebraic sums of the waves amplitudes of the QRS complex in leads I, III, and aVF, respectively.

There are other formulas for calculating the heart's electrical axis, while only a pair of standard leads is used for the calculation, for example, leads I and II or II and aVF [32-33].

The methods discussed above show that to calculate the heart's electrical axis it is necessary to take into account the amplitudes of the QRS complex waves in standard limb leads. At the same time, all these methods are unsuitable for automatic calculation of the QRS axis position, since, for their implementation, it is necessary to perform morphological analysis of an ECG and determine the waves amplitudes of the QRS complex in the corresponding leads.

Since the height of the waves in different leads depends on the direction of the heart's electrical axis, i.e. on the angle α, then the paper proposes to solve the inverse problem, i.e. calculate the position of the heart's electrical axis based on the change in the amplitudes in the standard leads from the limbs. With this approach, there is no need to find the amplitudes of the individual structural elements of an ECG, which means that there is no need to perform morphological analysis of each of the leads under consideration.

Number the main limb leads as follows: 1 – lead I, 2 – lead II, 3 – lead III, 4 – lead aVR, 5 – lead aVL, 6 – lead aVF.

To calculate the integral signal for all leads from the limbs in the work, it is proposed to average the leads taking into account the lead angle in the hexaxial reference system (Fig. 1), presenting each count by the following vector $\vec{S}_j = (S_{xj}, S_{yj})$:

$$\begin{cases} S_{xj} = \dfrac{1}{6}\sum_{i=1}^{6} Slead_{ij}\cos(-\beta_i); \\ S_{yj} = \dfrac{1}{6}\sum_{i=1}^{6} Slead_{ij}\sin(-\beta_i); \end{cases} \quad j = \overline{1,N}, \tag{4}$$

where: $Slead_{ij}$ is the value of the j-th count of the i-th lead; $\vec{\beta} = (0^0, 60^0, 120^0, -150^0, -30^0, 90^0)$ is the values vector of the leads angles in the hexaxial reference system.

In (4) there is a minus sign in front of the angle β_i due to the fact that the positive angles lie in the lower half-plane in the hexaxial reference system (Fig. 1).

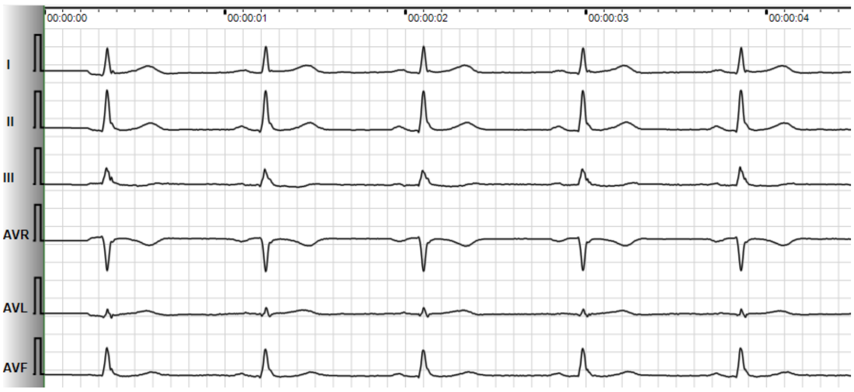
Then the angle θ_j and norm A_j of the vector $\vec{S}_j = (S_{xj}, S_{yj})$ can be calculated using the following expressions:

$$\theta_j = \mathrm{arctg}\frac{S_{yj}}{S_{xj}},$$

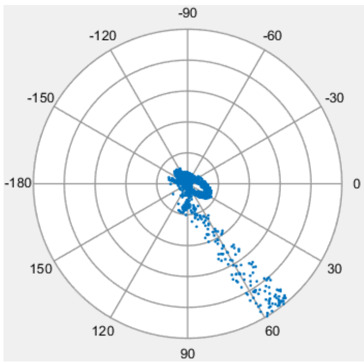
$$A_j = \sqrt{S_{xj}^2 + S_{yj}^2}.$$

In graphical form (in polar coordinates), the integral ECG signal is a figure predominantly elongated along the axis the direction of which coincides with the heart's electrical axis.

For example, in polar coordinates the integral signal of the electrocardiogram shown in Fig. 3a will have the form as in Fig. 3b.



a



b

Fig. 3. **The ECG (man, 43 years old, HR 67 bpm):**
a – the fragment of the normal ECG;
b – the integral signal in polar coordinate system
(the values of the angles coincide with the angles in the hexaxial reference system)
Source: **compiled by the authors**

From the analysis of the ECG in Fig. 3a, it can be concluded that the heart's electrical axis is normal, because $R_{II} > R_I > R_{III}$. It can be easily seen that the geometric point cloud in the polar coordinate system (Fig. 3b) is also elongated towards the angle 60^0.

If a vector is constructed with the origin at the reference point of polar coordinates and the end at the center of mass of the points most distant from the reference point, then this vector will show the direction of the heart's electrical axis.

To find the most distant points from the reference point, it is proposed to use cluster analysis, namely the *k*-means method [34]. In this case, one cluster should unite the points of the integral signal farthest from the reference point, and several clusters – all other points.

Thus, the following algorithm is proposed for calculating the heart's electrical axis based on the integral signal:

1) Using cluster analysis, we divide all points $\vec{S}_j = (S_{xj}, S_{yj})$ into K clusters with centers $\vec{C}_k(x_{k0}, y_{k0})$, $k = \overline{1, K}$.

It should be noted that the result of dividing the points by the *k*-means method strongly depends on which points were chosen as the centers of the clusters at the initial stage [35-36].

Therefore, it is necessary to set the initial centers of the clusters in such a way that the points farthest from the reference point are into one of the clusters, and all other points are distributed between the remaining clusters.

For this, the center of the 1st cluster will be considered the center of mass of 5 % of the points farthest from the reference point (i.e., with the maximum values of the norm). The initial centers of the remaining clusters will be considered the center of mass of 10 % of the points closest to the reference point.

2) We find the center of mass of the cluster farthest from the reference point

$$\vec{C}(x_0, y_0) = \vec{C}_m(x_{m0}, y_{m0}),$$

where $m = \arg\max_k \left|\vec{C}_k\right|$.

3) The direction of the heart's electrical axis is the angle between the OX axis and the vector $\vec{C} = (x_0, y_0)$:

$$QRSaxis = -\text{arctg}\,\frac{y_0}{x_0}. \quad (5)$$

In (5), the minus sign allows matching the angles of the polar and hexaxial reference systems.

To implement the method proposed in the article, a program was written in Matlab presented below:

```
% the values vector of
% the leads angles
% in the hexaxial reference system
LeadAngle=[0 60 120 -150 -30 90];

% recalculating the angle
% from degrees to radians
LeadAngle=LeadAngle*pi/180;

% integral signal calculation by (4)
LeadAxisX=Slead(1:6,:).*...
   repmat(cos(-LeadAngle),Nsignal,1)';
LeadAxisY=Slead(1:6,:).*...
   repmat(sin(-LeadAngle),Nsignal,1)';
Sx=mean(LeadAxisX,1);
Sy=mean(LeadAxisY,1);

% transition to polar coordinates
th=atan2(Sy,Sx);
A=(Sx.^2+Sy.^2).^0.5;

% sort by vector norm
[sort_A,sorti]=sort(A);

% finding the greatest vector norm
max_ln=sort_A(end);

% finding initial cluster centers
n1=round(0.95*Nsignal);
n2=round(0.1*Nsignal);
c1=[mean(Sx(sorti(n1:Nsignal)))...
   mean(Sy(sorti(n1:Nsignal)))];
c2=[mean(Sx(sorti(1:n2)))...
   mean(Sy(sorti(1:n2)))];

% cluster analysis
Kcl=5; % number of clusters
[ind,C]=kmeans([Sx' Sy'],Kcl,...
    'Start',[c1;repmat(c2,Kcl-1,1)]);

% calculating the QRS axis by (5)
normC=(C(:,1).^2+C(:,2).^2).^0.5;
[m,Im]=max(normC);
QRSaxis=-atan2(C(Im,2),C(Im,1));

% recalculating the angle
% from radians to degrees
QRSaxis=QRSaxis*180/pi;
```

To connect the developed module to the cardiological DSS "TREDEX telephone", the program was exported to a dynamic link library (DLL).

For the ECG shown in Fig. 3, using the above program, the heart's electrical axis was calculated which was 54^0, that corresponds to its normal position (Fig. 4). The obtained value of the heart's electrical axis is fully consistent with the conclusion of the cardiologist.

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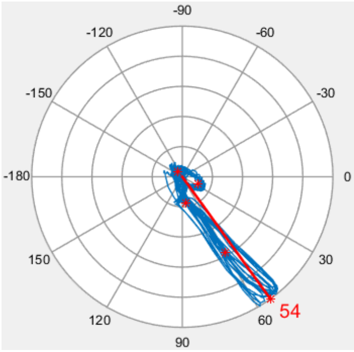


Fig. 4. **The integral ECG signal in a polar coordinate system with marked cluster centers and the heart's electrical axis**
Source: **compiled by the authors**

Studies have shown that, in terms of clustering errors, the optimal number of clusters $K = 5$.

This is explained by the fact that most of the points of the integral signal are located near the reference point (Fig. 3b), while they most often have three directions of angular coordinates; therefore, three clusters are intended for clustering these points (Fig. 4).

The fourth cluster is necessary for combining points located between the reference point and the points farthest from the reference point which, in turn, form the fifth cluster.

Examples of clustering for various integral signals of EGCs with different pathologies are shown in Fig. 5.

RESULTS OF AUTOMATIC SEARCH OF THE HEART'S ELECTRICAL AXIS FOR ECGs IN NORMAL AND WITH DIFFERENT PATHOLOGIES

Verification of the results was carried out using the database of electrocardiograms which were recorded using a transtelephone digital 12-channel electrocardiological complex "Telecard" (manufactured by TREDEX Company LLC, Kharkiv) and decoded by cardiologists of the communal non-profit enterprise of the Kharkiv Regional Council "Center for Emergency Medical aid and disaster medicine".

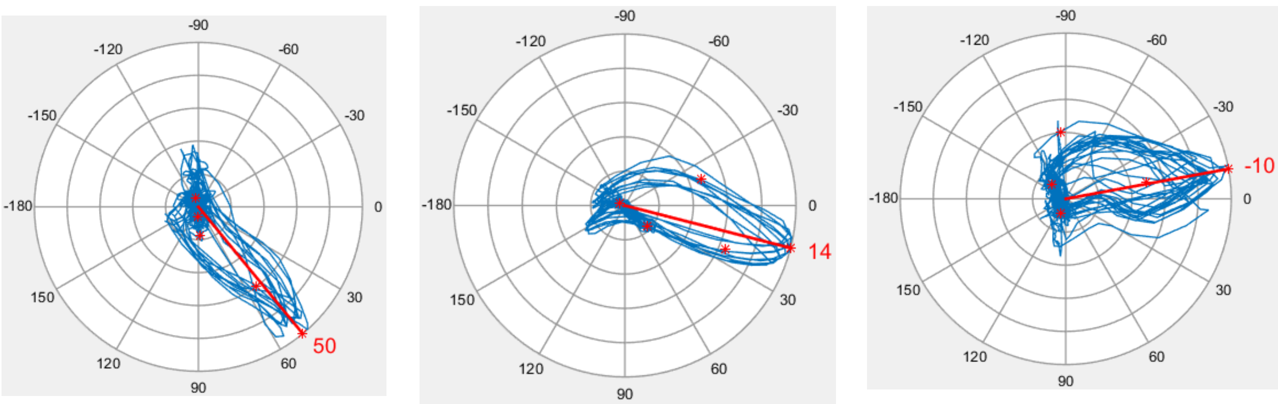
In total, 678 ECGs of all age categories (from 3 to 85 years old) are analyzed, of which 397 (58.55%) ECGs are recorded in men and 281 (41.45%) in women.

At the same time, 135 (19.91 %) ECGs are normal and 543 (80.09 %) ECGs have pathological changes, among which the following can be distinguished: 29 (5.34 %) – acute myocardial infarction; 35 (6.45 %) – postinfarction cardiosclerosis; 162 (29.83 %) – rhythm disturbances; 176 (32.41 %) – conduction disorders; 141 (25.97 %) – myocardial hypertrophy.

To verify the results of automatic calculation of the heart's electrical axis by real electrocardiograms using the proposed method, the developed program was exported in the Matlab language to DLL. The resulting DLL was connected to the existing cardiological DSS "TREDEX telephone" operating as part of the medical diagnostic complex "TREDEX".

Comparison of the results of calculating the ECGs by a doctor and automatically using the proposed method showed that in the overwhelming majority of cases (95.28 %) the decisions made coincide. At the same time, cardiologists make mistakes, and errors are made during automatic calculation using the proposed method.

The developed method made it possible to correct medical mistakes in the determination of the heart's electrical axis. Most often, such mistakes occur in the case of recording low-amplitude ECGs with various pathologies.



a b c

Fig. 5. **Examples of clustering for various integral signals:**
a – the ECG with first-degree atrioventricular block; b – the ECG with left ventricular hypertrophy; c – the ECG with paroxysmal supraventricular tachycardia
Source: **compiled by the authors**

For example, as the analysis result of the ECG with impaired intraventricular conduction (Fig.6a), the cardiologist defined the heart's electrical axis as horizontal. However, using the proposed method, it was calculated that the heart's electrical axis is located at an angle $\alpha = -10°$ (Fig. 6b), which was confirmed by a cardiologist upon repeated analysis. The reason for the mistake made by the cardiologist is related to the low amplitude of the recorded ECG.

For visual identification, the cardiologist used the following algorithm [13]:

1) The isoelectric QRS complex is recorded in standard lead aVF (Fig. 6a) which means that the heart's electrical axis is perpendicular to the axis of lead aVF.

2) According to the hexaxial reference system (Fig. 1), the axis perpendicular to the axis of the lead aVF is the axis of standard lead I which means that the heart's electrical axis is parallel to the axis of the lead I.

3) In lead I, the largest positive QRS complex is recorded (Fig. 6a), which means that the heart's electrical axis is horizontal.

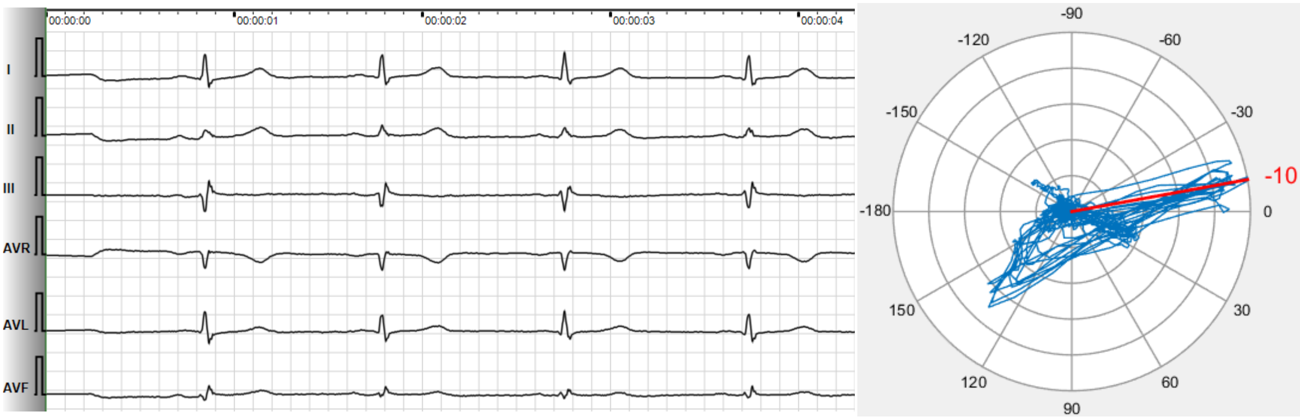
However, the QRS complex close to isoelectric is also recorded in standard lead II, and in lead aVL, the axis of which is perpendicular to the axis of lead II (Fig. 1), a positive QRS complex is recorded. In this case, the amplitudes of the QRS complexes in the standard leads aVL and I are comparable which leads to a shift of the heart's electrical axis to the left. When the heart's electrical axis was re-determined, the cardiologist confirmed that the axis was shifted to the left which coincided with the automatic calculation using the proposed method.

Errors in determining the heart's electrical axis using the developed method are observed either for ECGs with paroxysmal ventricular tachycardia, or for ECGs of low quality with various artifacts associated with incorrect signal registration.

Consider an example of the heart's electrical axis determination by the ECG with paroxysmal ventricular tachycardia (Fig. 7a). Detailed diagnosis of a cardiologist: ventricular tachycardia with a HR 187 bpm, the heart's electrical axis deviated to the left, complete left bundle branch block, signs of left ventricular hypertrophy, subendocardial damage in the lower, lateral region. With such pathology, it is obvious that the heart's electrical axis will be shifted to the left, but the automatic calculation gives a value $\alpha = 91^0$ (Fig. 7b) which corresponds to a slight deviation to the right. Such errors of automatic calculation are associated with the fact that with paroxysmal ventricular tachycardia, the QRS complex is significantly modified (Fig. 7a).

Now consider an example of determining the heart's electrical axis from the ECG of low quality with artifacts (Fig. 8a). In the second half of the signal, a significant baseline drift is observed. Detailed diagnosis of a cardiologist: supraventricular tachycardia with HR 150 bpm, the heart's electrical axis is semi-vertical, signs of hypertrophy of both ventricles. If the entire implementation of the ECG is taken into account, then automatically the heart's electrical axis is calculated incorrectly (Fig. 8b).

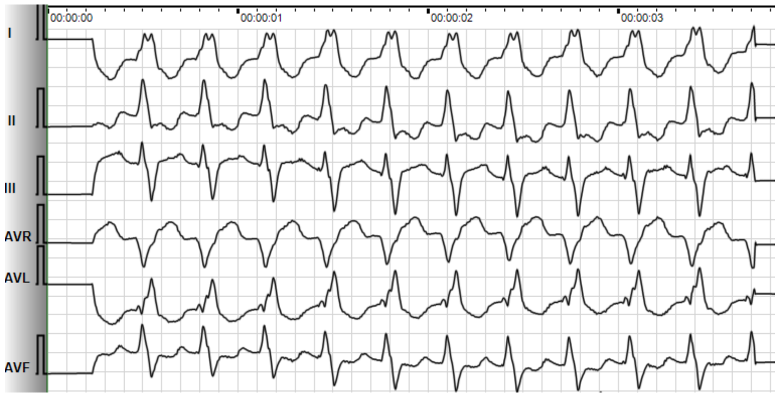
However, if the ECG section with a significant isoline drift is excluded for the calculation (in this case, take, for example, only the first half of the implementation) then the error of the automatic calculation of the heart's electrical axis can be avoided (Fig. 8c).



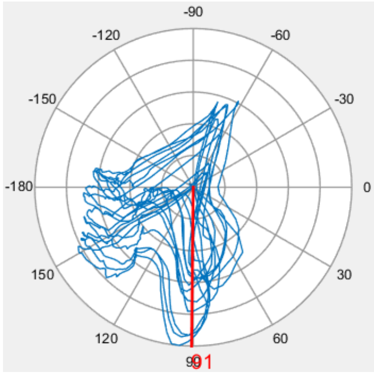
a b

Fig. 6. **The ECG with impaired intraventricular conduction (woman, 49 years old, HR 63 bpm): a – the ECG fragment; b – the integral signal and calculated heart's electrical axis**

Source: **compiled by the authors**

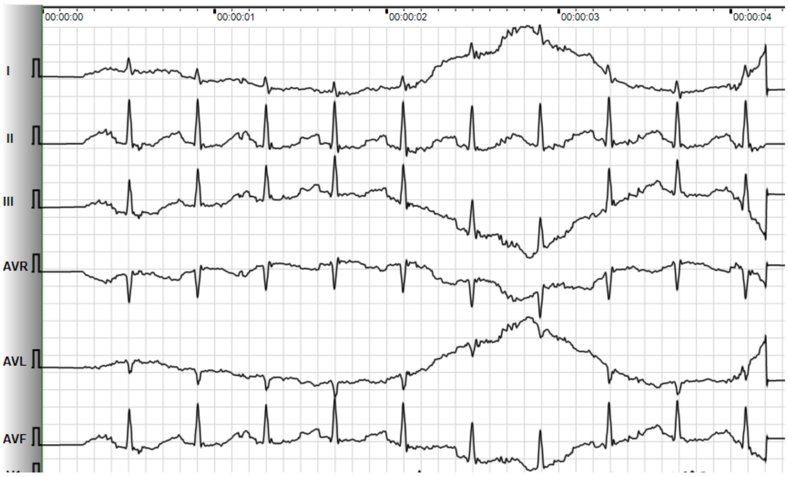


a

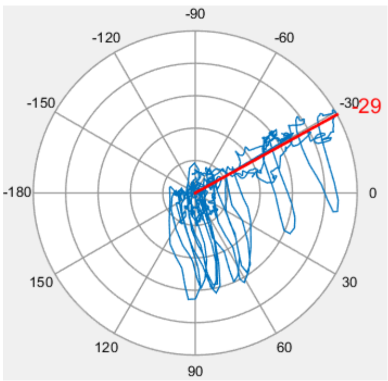


b

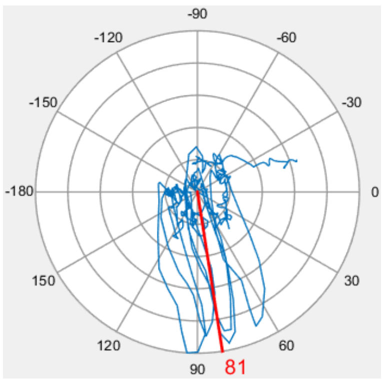
Fig. 7. **The ECG with paroxysmal ventricular tachycardia (man, 56 years old, HR 187 bpm): a – the ECG fragment; b – the integral signal and calculated heart's electrical axis (incorrect determination)**
***Source:* compiled by the authors**



a



b



c

Fig. 8. **The ECG with paroxysmal supraventricular tachycardia (man, 44 years old, HR 150 bpm): a – the ECG fragment with artifacts; b – the integral signal of the entire ECG implementation and calculated heart's electrical axis (incorrect determination); c – integral signal for ECG realization without artifact area and calculated heart's electrical axis (correct determination)**
***Source:* compiled by the authors**

In this case, there is the calculated value $\alpha = 81^0$, which is fully consistent with the decision taken by the cardiologist.

Thus, some of the errors that may occur when calculating the heart's electrical axis using the proposed method can be corrected by performing preliminary ECG processing in order to exclude from consideration areas with artifacts that are associated with incorrect signal registration.

CONCLUSIONS

The paper developed the method for automatic determination of the heart's electrical axis based on the integral signal calculation for six standard ECG leads, which will improve the quality of morphological analysis of the ECGs in cardiological decision support systems and reduce the number of medical mistakes. The proposed method makes it possible to determine the heart's electrical axis without the need to search and analyze QRS complexes which makes it possible to correctly calculate the heart's electrical axis even for complex clinical cases.

The authors have developed software for the module of automatic determination of the heart's electrical axis in the Matlab language. To connect the developed module to the cardiological decision support system "TREDEX telephone", which operates as part of the medical diagnostic complex "TREDEX" (manufactured by "Company TREDEX" LLC, Kharkiv), the program was exported to DLL.

In the work, the developed method was verified on real ECGs which were recorded using the 12-channel transtelephone digital electrocardiological complex "Telecard" that is part of the medical diagnostic complex "TREDEX", and transcribed by cardiologists of the communal non-profit enterprise of the Kharkiv Regional Council "Center for Emergency Medical aid and disaster medicine". Comparison of the results of calculating the heart's electrical axis according to the electrocardiogram by the doctor and automatically using the proposed method showed that in the overwhelming majority of cases the decisions made coincide. At the same time, cardiologists make mistakes, and errors are made during automatic calculation using the proposed method. The paper explains the reasons for these mistakes and errors.

Further studies are aimed at improving the proposed method for of automatic determination of the heart's electrical axis in cardiological decision support systems in order to reduce decision-making errors and the use of calculated heart's electrical axis for morphological analysis of ECG based on matched morphological filtration.

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МЕТОД АВТОМАТИЧНОГО ВИЗНАЧЕННЯ ЕЛЕКТРИЧНОЇ ОСІ СЕРЦЯ В КАРДІОЛОГІЧНИХ СИСТЕМАХ ПІДТРИМКИ ПРИЙНЯТТЯ РІШЕНЬ

Ганна Євгенівна Філатова[1)]
ORCID: http://orcid.org/0000-0003-1982-2322; filatova@khpi.edu.ua
Мохамад Фахс[1)]
ORCID: http://orcid.org/0000-0001-7776-3311; fahes_93mohamad@hotmail.com
[1)] Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, Харків, Україна

АНОТАЦІЯ

Робота присвячена вирішенню наукової-практичної задачі автоматизації розрахунку електричної осі серця для підвищення якості морфологічного аналізу біомедичних сигналів з локально зосередженими ознаками в кардіологічних системах підтримки прийняття рішень, що в свою чергу дозволяє знизити ймовірність лікарських помилок. В роботі показано, що існуючі методи визначення електричної осі серця вимагають виконання морфологічного аналізу електрокардіограми. Авторами запропонований метод автоматичного визначення електричної осі серця без необхідності попереднього аналізу електрокардіограми. Метод заснований на визначенні інтегрального сигналу у фронтальній площині по всьому відведенням від кінцівок з урахуванням кута відведення в гексаксіальній системі відліку. У графічному вигляді (в полярних координатах) інтегральний електрокардіологічний сигнал є фігура, переважно витягнута уздовж осі, напрямок якої збігається з електричною віссю серця. Розташування електричної осі серця обчислюється як кут між віссю стандартного відведення I і вектором, кінець якого знаходиться в центрі мас геометричного місця точок, які найбільш віддалені від початку координат. Для реалізації запропонованого в статті методу написана програма на мові Matlab, яка підключена у вигляді динамічної бібліотеки до кардіологічної системі підтримки прийняття рішень "TREDEX telephone", що працює в складі медичного діагностичного комплексу "TREDEX" виробництва ТОВ Компанія "TREDEX", м. Харків. Верифікація результатів проводилася з використанням бази даних електрокардіограм, які були записані за допомогою транстелефонної цифрового 12-канального електрокардіологічний комплексу «Телекард», що входить до складу медичного діагностичного комплексу "TREDEX", та розшифровані лікарями-кардіологами комунального некомерційного підприємства Харківської обласної ради «Центр екстреної медичної допомоги та медицини катастроф». Порівняння результатів розрахунку електричної осі серця по електрокардіограм лікарем і автоматично за допомогою запропонованого методу показав, що в переважній більшості випадків прийняті рішення збігаються. При цьому помилки допускають як кардіологи, так і автоматичний розрахунок за допомогою запропонованого методу. В роботі пояснені причини цих помилок.

Ключові слова: морфологічний аналіз; біомедичний сигнал; локально зосереджені ознаки; кардіологічні системи підтримки прийняття рішень; електрокардіограма; електрична ось серця; інтегральний електрокардіологічний сигнал; гексаксіальна система відліку

ABOUT THE AUTHOR

Anna E. Filatova – Dr. Sci. (Eng), Prof., Department of Computer Engineering and Programming, National Technical University "Kharkiv Polytechnic Institute". Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0003-1982-2322; filatova@khpi.edu.ua
National Technical University "Kharkiv Polytechnic Institute", 2, Kyrpychova Str., Kharkiv, Ukraine
***Research field*:** Morphological Analysis of Medical Signals and Images; Probability theory and Mathematical Statistics

Ганна Євгенівна Філатова – д-р техніч. наук, проф. кафедри Обчислювальної техніки та програмування Національного технічного університету «Харківський політехнічний інститут». вул. Кирпичова, 2, Харків, Україна

Mohamad Fahs – Graduate Student of the Department of Computer Engineering and Programming National Technical University "Kharkiv Polytechnic Institute". 2, Kyrpychova Str., Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0001-7776-3311; fahes_93mohamad@hotmail.com
***Research field*:** Probability theory and Mathematical Statistics; Design of Decision Support Systems in Medicine

Мохамад Факс– аспірант, кафедри Обчислювальної техніки та програмування Національного технічного університету «Харківський політехнічний інститут». вул. Кирпичова, 2, Харків, Україна