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Synthesis of an integral signal for solving the problem of morphological analysis of electrocardiograms

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ABSTRACT

This work is devoted to solving the scientific and practical problem of morphological analysis of electrocardiograms based on an integral biomedical signal with locally concentrated features. In modern conditions of introduction of telemedicine in the health care system of Ukraine the creation of cardiological decision support systems based on automatic morphological analysis of electrocardiogram is of particular importance. The authors proposed a method for synthesizing an integral electrocardiogram in the frontal plane from all limb leads, taking into account the lead angle in the hexaxial reference system and the position of the heart’s electrical axis, since integral electrocardiological signals allow to obtain more accurate results compared to conventional electrocardiogram, because they take into account the individual characteristics of patients, a wide variety of electrocardiogram waveforms and complexes, which is associated not only with the presence of pathological processes in the myocardium, but also with the position of the electrical axis of the heart, in particular, the electrocardiogram will not register a low-amplitude P wave in the II department in the case of a horizontal electrical axis, but it will be clearly visible on the integral signal. To implement the method proposed in the article, a program was written in the MATLAB language, , the high speed of computation and good optimization of which allow to obtain results much faster and more accurate than using traditional approaches, and using the MATLAB Runtime library, which does not require licensing and is distributed free of charge, it was possible to provide more economical development, as well as to implement interaction with popular operating systems, which makes it more accessible and versatile. 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”. The paper shows that the proposed method for the synthesis of an integral signal with locally concentrated features will improve the quality of morphological analysis of electrocardiograms in cardiological decision support systems.

Keywords: Morphological analysis; biomedical signals; locally concentrated features; integral electrocardiogram; heart’s electrical axis; cardiological decision support system

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INTRODUCTION

Telemedicine has become widespread in connection with the health care system reform in Ukraine. On April 1, 2020, the second stage of medical reform started in Ukraine. This stage involves the development and introduction of modern technologies for medical care in rural areas, in particular with the use of telemedicine, especially if distance and time are critical factors for the provision of medical care, the implementation of adequate resource support for the implementation of medical care using telemedicine, telemedicine consultations in the “doctor-doctor” format, which aims to ensure equal access to quality medical services for patients from any part of the country [1].

The Telemedicine project involves the provision of medical services in four nosologies [2]:

- cardiovascular;
- endocrinological;
- respiratory diseases;
- dermatological.

Thus, one of the effective areas of telemedicine application is cardiology. At the same time, for the introduction of telemedicine into cardiology, it is necessary to develop new and improve existing medical diagnostic systems, which include cardiological decision support systems (DSS), for example, the medical diagnostic complex "TREDEX", consisting of specialized equipment and cardiological DSS "TREDEX telephone" (produced by TREDEX Company LLC, Kharkiv) [3].

ANALYSIS OF LITERARY DATA

The most common way to diagnose the state of the heart and cardiovascular system is morphological analysis of an electrocardiogram (ECG) [4, 5] with the subsequent analysis of the amplitude-time characteristics of found waves and complexes [6, 7] their shapes [8, 9]. The main advantages of electrocardiography are high diagnostic ability to detect many acute or chronic cardiovascular pathologies (coronary heart disease, acute myocardial infarction, pulmonary thromboembolism, etc.), to detect heart rhythm and conduction disorders (various types of arrhythmias) and the accessibility, safety and harmlessness of the method.

It should be noted that the ECG is a biomedical signal (BMS) with locally concentrated features (LCF), i.e. it is a signal with a structure in which diagnostic features are concentrated on small fragments of their definition area [10].

The main structural elements of the ECG that characterize the work of the myocardium are the P, Q, R, S, and T waves. Usually, the ECG is recorded using 12 standard leads. In cardiological practice, all basic calculations of the amplitude-time characteristics of structural elements are usually carried out in lead II (Fig. 1).

It should be noted that ECG even in norm is characterized by variability, which depends on age, sex, anatomical and constitutional features of the person and other factors. And exactly the correct interpretation of graphic representation of heart activity, carried out by the doctor of functional diagnostics, analysis of ECG waves, intervals, allows making the correct clinical assessment and differential diagnostics.

The task of the morphological analysis of BMS with LCF is to isolate informative fragments (structural elements) of the signal against the background of noise [10, 11].

In medical practice, an ECG decoding scheme has been adopted with a sequential study of the main aspects of the heart [12, 13]:

1. Determining the source of the pacemaker (it is performed based on morphological analysis of the P waves and QRS complexes).

2. Determination of heart rate and rhythm regularity (it is performed based on morphological analysis of the R waves).

3. Conduction analysis (it is performed based on morphological analysis of P waves and QRS complexes).

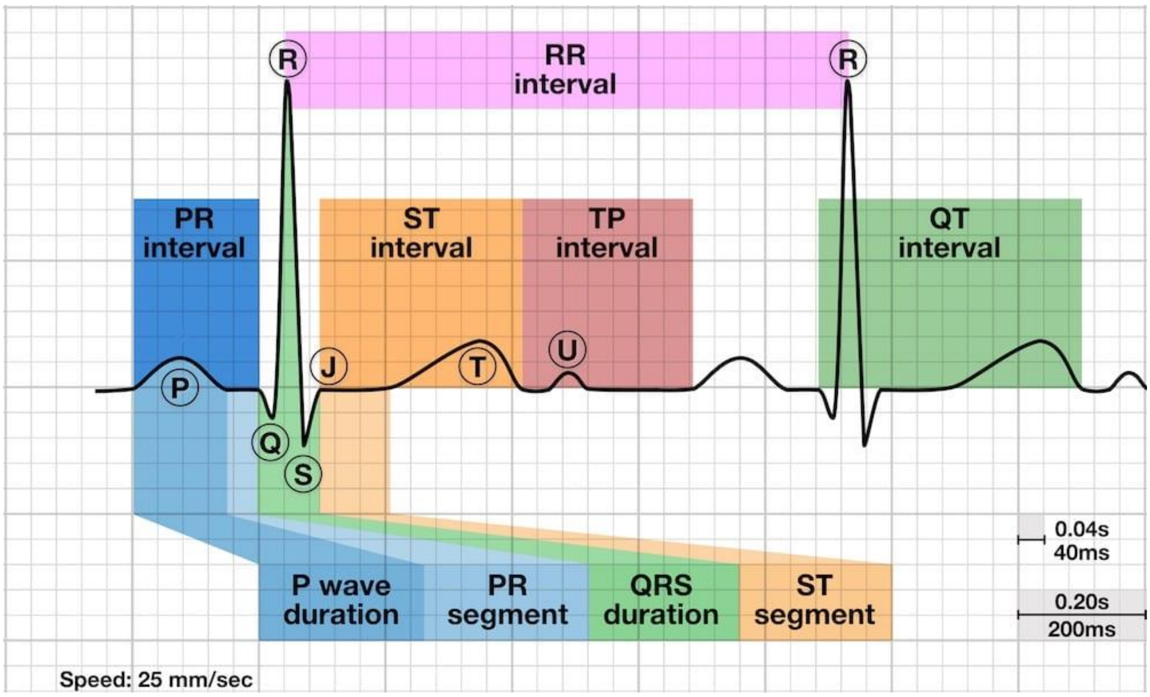


Fig. 1. **The ECG waveform and segments in lead II (a normal cardiac cycle)**
Source: **https://litfl.com/st-segment-ecg-library/**

4. Determination of the position of the heart's electrical axis (it is performed based on morphological analysis of QRS complexes).

5. Analysis of waves and intervals (it is performed based on morphological analysis of all structural elements).

It is easy to see from the above scheme that not a single step of ECG analysis is completed by without morphological analysis of the signal. As noted above, in the context of the introduction of telemedicine into the health care system of Ukraine, the creation of cardiological DSSs based on automatic morphological ECG analysis is of particular importance, for which various methods are used:

- ECG analysis in the time domain using various classification methods, including probabilistic classification [14, 15], cluster analysis and pattern recognition [16, 17], neural networks [18, 19], fuzzy clustering [20, 21] and others;
- ECG analysis in the time-frequency domain, for example, local (window) Fourier transform (spectral-time mapping) and wavelet transform [22, 23], as well as in the phase plane [10, 24];
- morphological filtration of ECG using the multichannel matched morphological filter proposed by the authors [25].

Despite the large number of works devoted to automatic ECG analysis [26, 27], the problem of improving the quality of automatic morphological analysis of biomedical signals remains relevant, especially in the case of a significant deviation of the analyzed ECG from the norm [28, 29].

In addition, the shape of the main ECG waves in one or another standard lead is also significantly influenced by the location of the heart's electrical axis (QRS axis). This is due to the fact that if the average electric vector of the heart (or the QRS axis) makes an acute angle with the positive direction of the lead axis then a positive complex is recorded on the corresponding lead, and if it is dull – a negative one 0. If the QRS axis is perpendicular to the lead axis then an equiphasic and/or isoelectric complex is recorded on the corresponding lead.

Thus, computer analysis of the ECG is complicates a wide variety of shapes of ECG waves and complexes, which is due not only to the presence of pathological processes in the myocardium, but also to the position of the heart's electrical axis.

FORMAL PROBLEM STATEMENT

The aim of the work is to improve the quality of automatic morphological analysis of ECG based on an integral biomedical signal with locally concentrated features in cardiological decision support systems.

To achieve this goal, the following tasks are solved:

- to develop a method for the synthesis of an integral electrocardiological signal based on all standard limb leads taking into account the angles of leads in the hexaxial reference system and the position of the heart's electrical axis;
- to develop software of synthesis module of the integral electrocardiogram for cardiological decision support system;
- to perform verification of the developed method with real electrocardiograms.

SYNTHESIS OF AN NTEGRAL ELECTROCARDIOLOGICAL SIGNAL

Normally, the heart's electrical axis is located at an angle from $+30°$ to $+69°$. In this case, the axis of lead II practically coincides with the QRS axis, therefore, as noted above, the main calculations are performed according to the amplitude-time parameters of the waves of lead II.

However, the deviation of the heart's electrical axis from the normal position is not in itself a sign of pathology but can significantly affect shape of the waves in all standard leads. So, for example, if the QRS axis is significantly deviated to the left (counterclockwise) or to the right (clockwise) then an equiphase QRS complex is recorded in lead II (Fig. 2). In this case, calculations can be carried out, for example, by lead I.

The method of calculating the heart's electrical axis proposed by the authors in 0 is used for the synthesis of an integral electrocardiological signal based on all standard limb leads taking into account the angles of leads in the hexaxial reference system and the position of the QRS axis. Number the standard limbs leads from 1 to 6 in the order they are listed: I, II, III, aVR, aVL, aVF.

Average the leads taking into account the lead angle in the hexaxial reference system (Fig. 3) presenting each count by the following vector $\overrightarrow{S_j} = (S_{xj}, S_{yj})$:

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

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

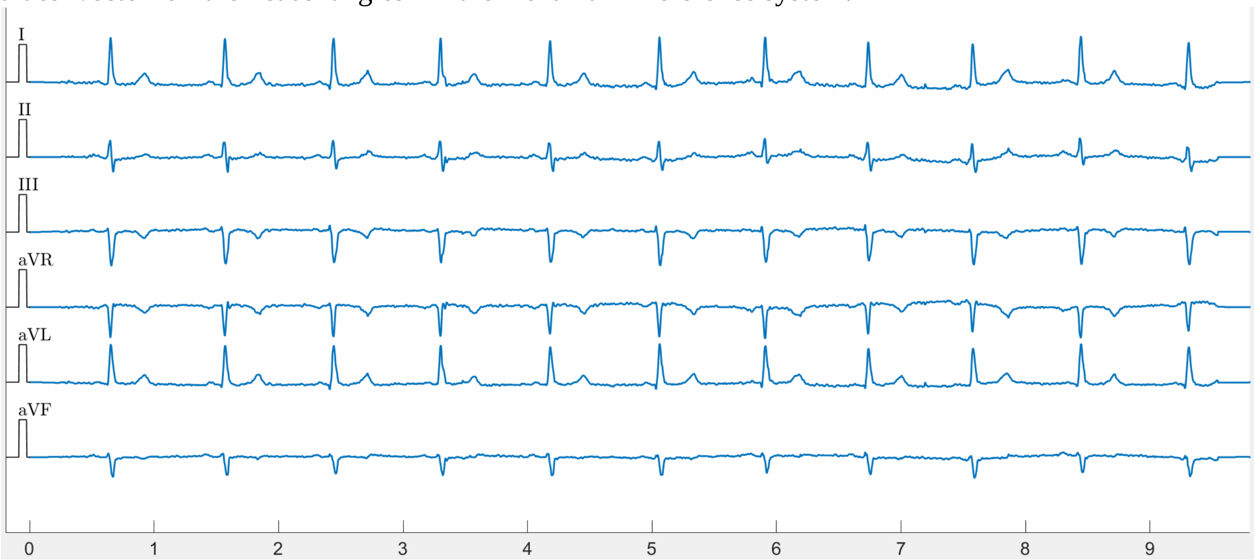


Fig. 2. **Fragment of the normal ECG**
(woman, 60 years old, HR 68 bpm, the heart's electrical axis $-11°$**)**
Source: **compiled by the authors**

In (1) the angles $\overrightarrow{\beta}$ are taken into account with a minus sign to match the polar and hexaxial reference systems.

Then the angle θ_j and norm A_j of the vector $\overrightarrow{S_j}=\left(S_{xj},S_{yj}\right)$ can be calculated using the following expressions:

$$\theta_j = arctg2(S_{xj},S_{yj}) = \\ = \begin{cases} \tan^{-1}\dfrac{S_{yj}}{S_{xj}}, & S_{xj}>0; \\ \tan^{-1}\dfrac{S_{yj}}{S_{xj}}+180°, & S_{xj}\le 0, S_{yj}\ge 0; \\ \tan^{-1}\dfrac{S_{yj}}{S_{xj}}-180°, & S_{xj}<0, S_{yj}<0; \\ 90°, & S_{xj}>0; \\ -90°, & S_{yj}<0; \end{cases} \quad (2)$$

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

All points $\overrightarrow{S_j}=(S_{xj},S_{yj})$ are divided into K clusters with centers $\overrightarrow{C_k}=(x_{k0},y_{k0})$, $k=\overline{1,K}$, using cluster analysis. Studies have shown that, in terms of clustering errors, the optimal number of clusters $K=5\ 0$.

The center of mass of the cluster farthest from the reference point is found:

$$\overrightarrow{C}(x_0,y_0)=\overrightarrow{C_m}(x_{m0},y_{m0})\,,$$

where $m=\arg\max_k|\overrightarrow{C_k}|$.

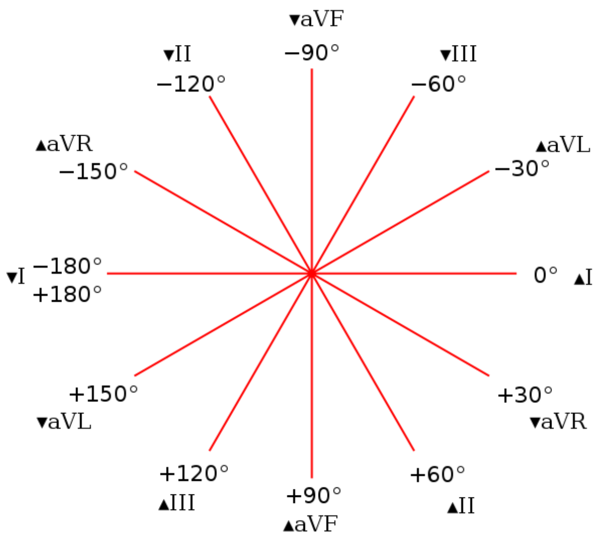


Fig. 3. **The hexaxial reference system**
Source: **https://en.wikipedia.org/wiki/Hexaxial_reference_system**

The direction of the heart's electrical axis in polar reference system is determined using the expression (2):

$$QRSaxis = arctg2(x_0,y_0)\,. \quad (3)$$

Knowing the direction of the heart's electrical axis, it is possible to calculate an integral signal, for which it is necessary to rotate the polar reference system by the angle $QRSaxis$.

Then in the new coordinate system $X'OY'$, the coordinates $\overrightarrow{S_j}=(S_{xj},S_{yj})$ of the original system

XOY obtained from (1) are calculated by the known expressions:

$$S'_{xj} = S_{xj}\cos QRSaxis + S_{yj}\sin QRSaxis; \qquad (4)$$

$$S'_{yj} = -S_{xj}\sin QRSaxis + S_{yj}\cos QRSaxis. \qquad (5)$$

Since in the new coordinate system the axis OX' coincides with the heart's electrical axis, taking into account the angles of the leads in the hexaxial reference system and the position of the QRS axis the integral signal is determined by (4):

$$Sint_j = S'_{xj}.$$

The points of the perpendicular axis OY' obtained by (5) represent the isoelectric complex and are not used in further calculations.

Since the positive axis of lead II coincides with the normal position of the QRS axis, then after turning the polar reference system by the angle $QRSaxis$, the integral signal $Sint_j$ will have a standard waveform of lead II, i.e. P, R, T waves will be positive and Q, S waves will be negative.

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]*pi/180;
% integral signal calculation by (1)
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
normC=(C(:,1).^2+C(:,2).^2).^0.5;
[m,Im]=max(normC);
% the heart’s electrical axis
% in polar coordinates
QRSaxis=atan2(C(Im,2),C(Im,1));
% integral signal calculation by (4)
Sx1=(Sx*cos(QRSaxis)+Sy*sin(QRSaxis));
Sint=Sx1.
```

The use of MATLAB makes it possible to significantly reduce the time for the development of software for specialized modules of the developed cardiological DSS, allowing us to focus on the development of the algorithm.

High computation speed and good optimization make it possible to get results much faster and more accurate than using traditional approaches such as spreadsheets or using programming languages such as C/C ++, Java, Pascal, or so on, without sacrificing computational accuracy. The MATLAB core makes it as easy as possible to work with vectors and matrices of both real and complex data types. All MATLAB core built-in functions are designed and optimized by experts and work faster or in the same way as their C/C ++ equivalent.

In addition, using MATLAB (together with the client part – Parallel Computing Toolbox), it is possible to build a complex of distributed computing of the client-server type, which allows us to develop distributed applications, transfer data to the server and control their execution in networks with distributed computing resources. The advantage of this approach can be considered the simplification of further development, debugging and optimization of real decision-making systems.

Another advantage of the MATLAB package is the ability to export the developed algorithm into a dynamic link library (DLL) for using the system code as an independent development with the ability to connect to third-party data processing and visualization complexes. Despite the fact that the difficulty of integrating the MATLAB library with C++ and JAVA applications is often noted as disadvantages, we managed to overcome this complexity and create an application that has all the positive qualities that an application can provide using modules and algorithms provided by MATLAB.

It should be noted that using MATLAB it is possible to create DLL not only for applications running under the Windows operating system, but also for applications running under *NIX operating system by installing MATLAB Compiler Runtime. MATLAB Compiler Runtime compiles the developed code into an executable library that can be used to write applications for a specific operating system. A significant advantage of the MATLAB Runtime library is that it does not require licensing and is distributed free of charge, which makes it possible to significantly reduce the financial costs of developing a cardiological DSS.

Therefore, to connect the developed module to the cardiological DSS "TREDEX telephone", the program was exported to a dynamic link library.

EXPERIMENTS AND RESULTS

Verification of the results was carried out using the database of electrocardiograms which were recorded using the transtelephone digital 12-channel electrocardiological complex "Telecard" (produced by TREDEX Company LLC, Kharkiv). To verify the results, a number of experiments were performed on the synthesis of integral signals for normal ECGs with different QRS axis positions. 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.

Fig. 4 shows a normal ECG with a normal position of the QRS axis and the corresponding integral signal. It is easy to see here that the synthesized integral signal has a waveform of lead II, i.e. positive P, R, T waves and negative Q, S ones (Fig. 1).

As noted earlier, if the QRS axis is deviated to the left then the equiphase QRS complex is recorded in lead II (Fig. 2), while calculations have to be made in other lead, which can significantly complicate automatic morphological analysis of the ECG. However, the integral signal (Fig. 5) synthesized for the ECG shown in Fig. 2 shape as a standard waveform of lead II. This allows to time mark the signal using the synthesized integral signal.

Fig. 6 shows the normal ECG with the horizontal heart's electrical axis and the corresponding integral signal. It is easy to see that due to the horizontal position of the QRS axis, a low-amplitude P wave is not recorded in lead II (Fig. 6a). At the same time, the boundaries of the P wave are clearly visible on the integral signal (Fig. 6b), which, as in the previous case, has shape as a standard waveform of lead II.

b

Fig. 4. **The normal ECG (man, 43 years old, HR 67 bpm, the heart's electrical axis +54°): a – signal fragment; b – the integral signal**
Source: **compiled by the authors**

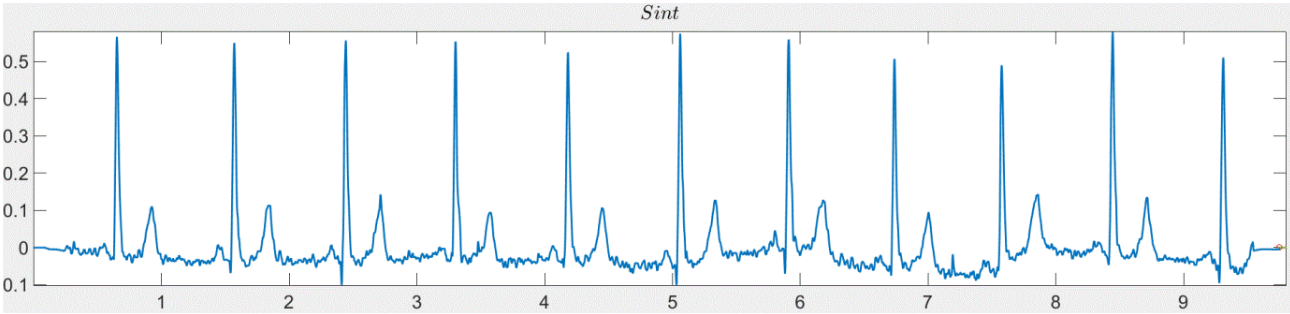
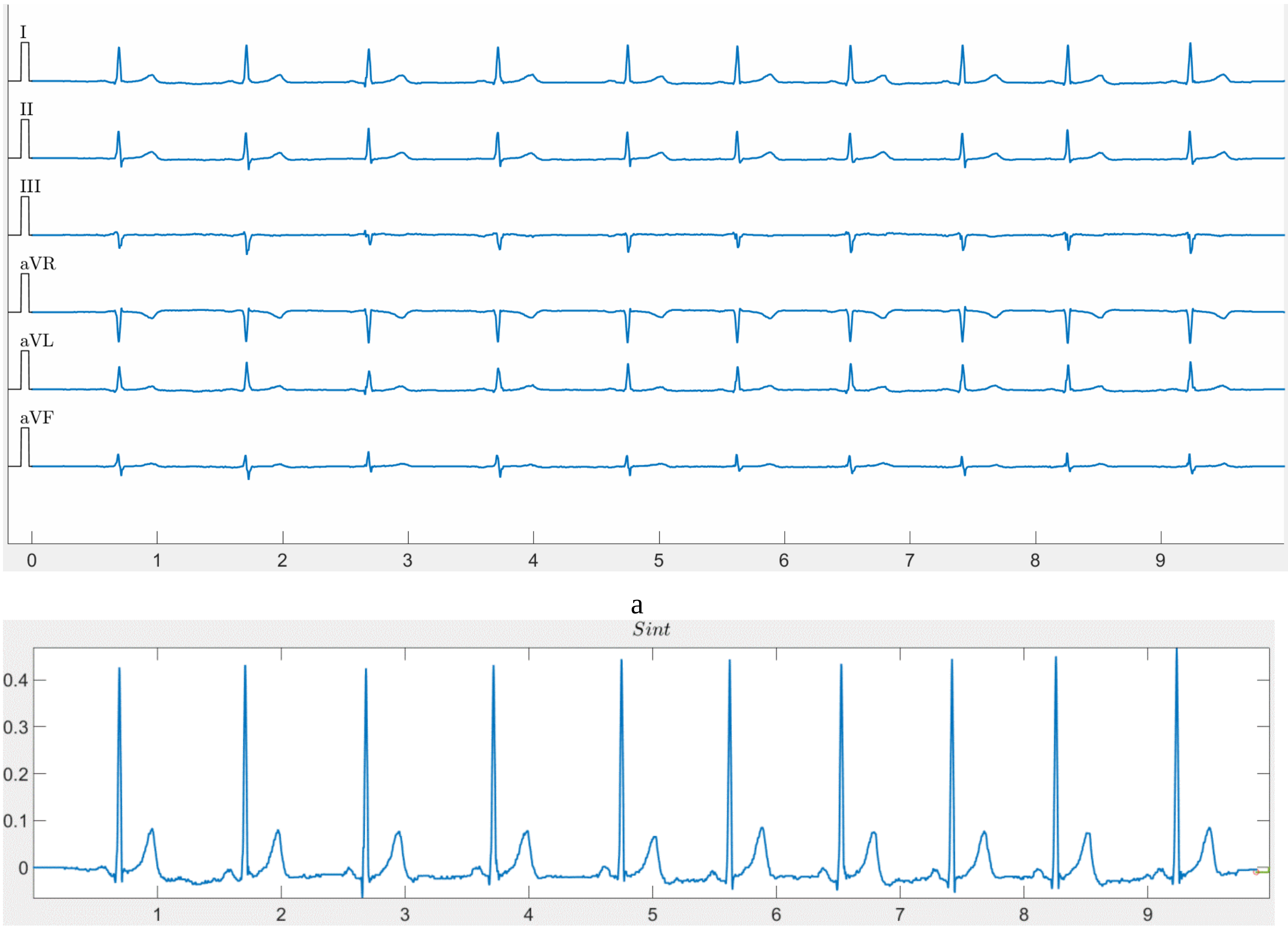


Fig. 5. **The integral signal synthesized by normal ECG with the heart's electrical axis** $-11°$
Source: **compiled by the authors**



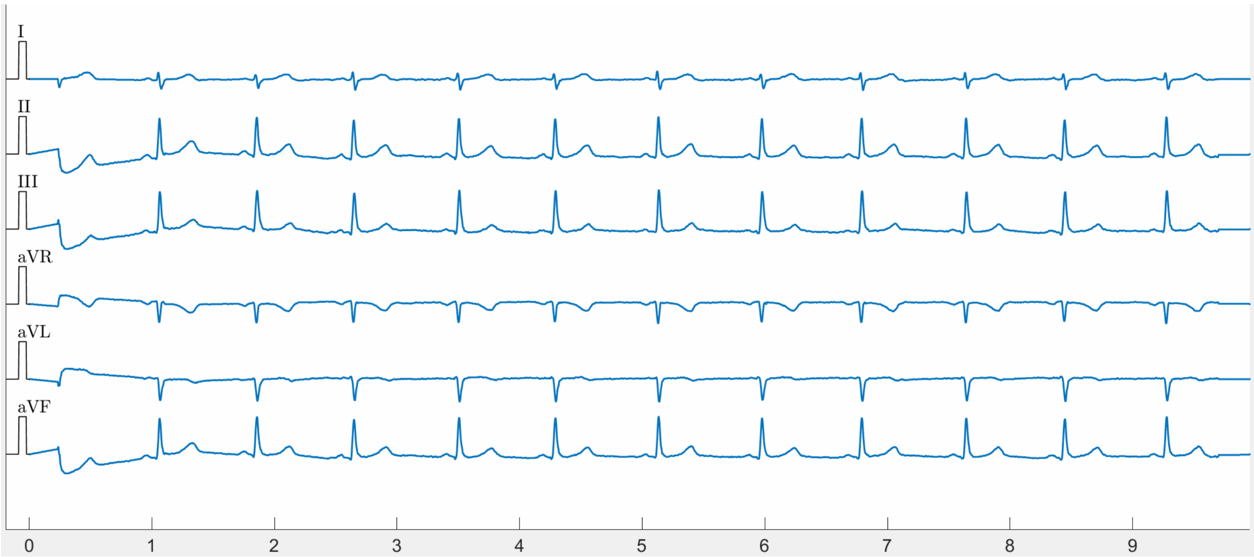
a

b

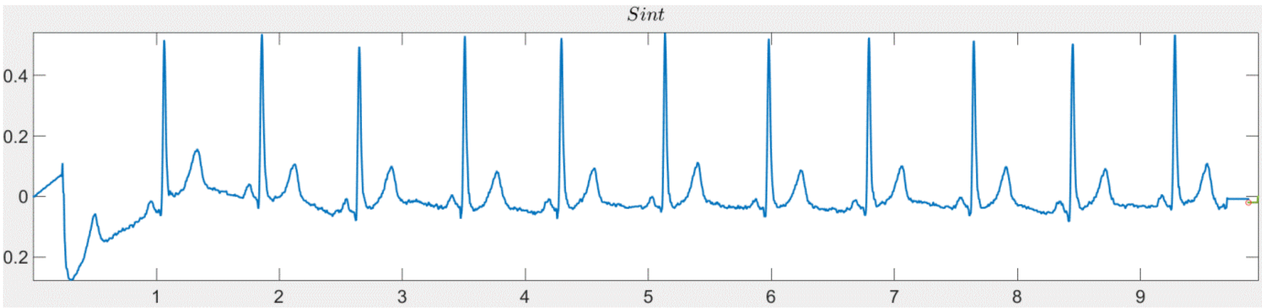
Fig. 6. **The normal ECG (man, 31 years old, HR 63 bpm, the heart's electrical axis** $+14°$**):**
a – signal fragment; b – the integral signal
Source: **compiled by the authors**

This makes it easy to perform automatic detection of this structural element, which is impossible to do with lead II.

Fig. 7 shows the normal ECG with the QRS axis deviated to the right and the corresponding integral signal. This experiment also synthesizes the integral signal that has the waveform typical for lead II. Analysis of the integral signals synthesized from normal ECGs with different values of heart's electrical axis showed that the amplitude characteristics of the structural elements of various integral signals are comparable, which makes it possible to determine the general indicators of the norm.



a



b

Fig. 7. **The normal ECG (woman, 12 years old, HR 73 bpm, the heart's electrical axis $+95°$): a – signal fragment; b – the integral signal**

Source: **compiled by the authors**

CONCLUSION

The scheme of ECG transcripts with consecutive studying of the main aspects of the heart's work is analyzed in the work. It is noted, that at all stages of decoding: (definition of a rhythm driver; definition of heart rate and rhythm regularity; conductivity analysis; definition of position of an electric axis; analysis of waves and intervals) the morphological analysis of various elements of ECG signal is carried out.

There are considered the task (separation of informative structural elements of the signal on the background of disturbances) and peculiarities of morphological analysis of electrocardiograms for subsequent diagnostics of cardiovascular diseases. It is noted that in cardiological practice, ECG registration is performed according to 12 standard leads. The shape of the main ECG waves in a particular standard lead is significantly influenced by the location of the electrical axis of the heart.

Normally, the electrical axis of the heart is located at an angle from $+30°$ to $+69°$. In this case, the axis of lead II practically coincides with the electrical axis of the heart, so the main calculations are performed according to the amplitude-time parameters of lead II waves. However, deviation of the electrical axis of the heart from its normal position is not a sign of pathology in itself, but may significantly affect the appearance of the waves in all standard leads.

If the electrical axis of the heart is deflected to the left, an equiphase QRS complex is recorded at lead II, and the calculations have to be performed using another lead, for example, lead I, which significantly complicates the automatic morphological analysis of the ECG. Proceeding from the above stated, the relevance of detecting electrical axis of the heart already at the first stage of ECG transcription and synthesis of the integral electrocardiological signal, which is directed along the electrical axis of the heart on the basis of analysis of the available signals of 12 standard leads is substantiated in this work.

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The integral electrocardiological signal thus obtained is used for further ECG interpretation instead of lead II in the traditional approach.

A method for synthesis of the integral electrocardiological signal from all limb leads taking into account the lead angles in the hexaxial reference system and the position of the cardiac electrical axis has been developed, which will improve the quality of morphological analysis of ECG in cardiac decision support systems and reduce the number of medical errors.

The authors have developed software for the module of synthesis of integral electrocardiogram in MATLAB. To connect the developed module to the cardiological decision support system "TREDEX telephone", which works as part of the medical diagnostic complex "TREDEX" (produced by the "TREDEX" company, Kharkov), exported the program to DLL.

Verification of the developed method was performed in this work on real ECGs, which were recorded with the transtelephonic digital 12-channel electrocardiological complex "Telecard", which is part of the medical diagnostic complex "TREDEX".

To verify the results, a number of experiments on the synthesis of the integral signal for ECG in norm with different positions of electrical axis of the heart were performed.

It was shown, that at different positions of electrical axis of the heart, the synthesized integral signal has the standard appearance for lead II, i.e. positive P, R, T waves and negative Q, S waves. The amplitude characteristics of the structural elements of different integral signals are commensurable, which enables to determine general indexes of the norm. And it is recommended to use this signal for the automatic morphological analysis of ECG.

Further researches are aimed to study morphological properties of integral signal for ECG with different pathologies in order to enhance morphological analysis of ECG in cardiological decision support systems.

REFERENCES

1. "Law of Ukraine on improving the availability and quality of medical care in rural areas" (in Ukrainian). – Available from: https://zakon.rada.gov.ua/laws/show/2206-19#Text. – [Accessed: Dec. 2021].

2. Voronenko, Yu. V., Orabina, T. M., Moiseienko, R. I. et al. "Methodical recommendations for diagnosis and treatment of some diseases in the provision of telemedicine services (for general practitioners – family medicine)" (in Ukrainian). *Publ. Shupyk National Medical Academy of Postgraduate Education*. Kyiv: Ukraine. 2019. 104 p. – Available from: https://moz.gov.ua/uploads/2/14076-a5_2019_moz_shupik_forweb.pdf. – [Accessed: Feb. 2021].

3. Pavlovich, R. V. "All-Ukrainian telemedicine network of remote ECG diagnostics "Telecard": year 2017" (in Russian). – Available from: http://www.tredex-company.com/ru/publications/ electrocardiography. *Title from the screen*. – [Accessed: Feb. 2021].

4. Hossain, B., Bashar, S. K., Walkey, A. J., McManus, D. D. & Chon, K. H. "An accurate QRS complex and P wave detection in ECG signals using complete ensemble empirical mode decomposition approach". *IEEE Access*. 2019; 7: 128869–128880. DOI: https://doi.org/10.1109/ACCESS.2019.2939943.

5. Kaur, A., Agarwal, A., Agarwal, R. & Kumar, S. "A novel approach to ECG R-Peak detection". *Arab J Sci Eng*. 2019; 44: 6679–6691. DOI: https://doi.org/10.1007/s13369-018-3557-8.

6. Ribeiro, A. H., Ribeiro, M. H., Paixão, G. M. M. et al. "Automatic diagnosis of the 12-lead ECG using a deep neural network". *Nat Commun*. 2020; 11 (1): 1760. DOI: https://doi.org/10.1038/s41467-020-15432-4.

7. Mattu, A., Tabas, J. A. & Brady, W. J. "Electrocardiography in emergency, acute and critical care". *Publ. American College of Emergency Physicians (ACEP)*; 2nd edition: 2019. 330 p.

8. Brady, W. J., Lipinski, M. J. et al. "Electrocardiogram in clinical medicine". *Wiley-Blackwell*; 1st edition: 2020. 512 p.

9. Hampton, J. "The ECG made practical". *Elsevier*; 7th edition. 2019. 384 p.

10. Fainzylberh, L. S. "A generalized method for processing cyclic signals of complex shape in a multidimensional parameter space" (in Russian). *International Scientific and Technical Journal "Problems of control and informatics"*. 2015; 2: 58–71.

11. Shcherbakova, G. Yu., Krylov, V. N. & Plachinda, O. E. "Determination of characteristic points of electrocardiograms using multi-start optimization with a wavelet transform". *Herald of Advanced*

Information Technology. *Publ. Nauka i Tekhnika*. Odessa: Ukraine. 2020; 3 (2): 23–33. DOI: https://doi.org/10.15276/hait.02.2020.2.

12. Kligfield, P., Gettes, L. S., Bailey, J. J. et al. "Recommendations for the standardization and interpretation of the electrocardiogram. Part I: The electrocardiogram and its technology: a scientific statement from the American Heart Association Electrocardiography and Arrhythmias Committee, Council on Clinical Cardiology; the American College of Cardiology Foundation; and the Heart Rhythm Society". *Circulation*. 2007; 115: 1306–1324. DOI: https://doi.org/10.1016/j.jacc.2007.01.024.

13.Ashcheulova, T. V., Kovaleva, O. N. & Safargalina-Kornilova, N. A. "Electrocardiographic research method. Method of registration and decoding of electrocardiogram" (in Russian). *Kharkiv National Medical University*. Kharkiv: Ukraine. 2016: 16 p.

14. Ruvinskaya, V. M., Shevchuk, I. & Michaluk, N. "Models based on conformal predictors for diagnostic systems in medicine". *Applied Aspects of Information Technology*. *Nauka i Tekhnika*. Odessa. Ukraine: 2019; 2 (2): p. 127–137. DOI: https://doi.org/10.15276/aait.02.2019.4.

15. Vishwanath, B., Pujeri, R. V. & Devanagavi, G. "Probabilistic principal component analysis-based dimensionality reduction and optimization for arrhythmia classification using ECG signals". *Bio-Algorithms and Med-Systems*. 2019; 15 (1): 20180037. DOI: https://doi.org/10.1515/bams-2018-0037.

16. Landauskas, M. & Ragulskis, M. "Clustering of ECG segments for patients before sudden cardiac death based on Lagrange descriptors". *Vibroengineering PROCEDIA*. 2019; 26: 78–83. DOI: https://doi.org/10.21595/vp.2019.21007.

17. Pasollia, E. & Melgani, F. "Genetic algorithm-based method for mitigating label noise issue in ECG signal classification". *Biomedical Signal Processing and Control*. 2015; 19: 130–136. DOI: https://doi.org/10.1016/j.bspc.2014.10.013.

18. Khan, A., Khan, A. H., Hussain, M. & Malik, M. K. "Arrhythmia Classification Techniques Using Deep Neural Network". *Complexity*. 2021; 2021: 9919588. DOI: https://doi.org/10.1155/2021/9919588.

19. Ribeiro, A. H., Ribeiro, M. H., Paixão, G. M. M., et al. "Automatic diagnosis of the 12-lead ECG using a deep neural network". *Nature Communications*. 2020: Vol. 11: 1760. DOI: https://doi.org/10.1038/s41467-020-15432-4.

20. Dalal, S. & Vishwakarma, V. P. "Classification of ECG signals using multi-cumulants based evolutionary hybrid classifier". *Sci Rep*. 2021; 11: 15092. DOI: https://doi.org/10.1038/s41598-021-94363-6.

21. Doğan, B. & Korürek, M. "A new ECG beat clustering method based on kernelized fuzzy c-means and hybrid ant colony optimization for continuous domains". *Applied Soft Computing*. 2012; 12 (11): 3442–3451. DOI: https://doi.org/10.1016/j.asoc.2012.07.007.

22. Dubrovin, V. I., Tverdohleb, J. V. & Kharchenko, V. V. "Automated system for the analysis and interpretation of ECG". *Radio Electronics, Computer Science, Control*. 2014: 1 (30): 150–157. DOI: https://doi.org/10.15588/1607-3274-2014-1-22.

23. Kolomejzewa, A. W., Mischugowa, G. W., Mul, A. P. & Rjabych, G. Ju. "Application of wavelet transform and Proni method for identification of biogenic signals" (in Russian). *Herald of DSTU*. 2010: Vol. 10 No. 4: 455–465.

24. Fainzilberg, L. S. "New approaches to the analysis and interpretation of the shape of cyclic signals". *Cybernetics and Systems Analysis.* 2020; 56 (4): 665–674. DOI: https://doi.org/10.1007/s10559-020-00283-0.

25. Povoroznyuk, A. I., Filatova, A. E., Zakovorotniy, A. Yu. & Shehna, Kh. "Development of method of matched morphological filtering of biomedical signals and images". *Automatic Control and Computer Sciences*. 2019; 53 (3): 253–262. DOI: https://doi.org/10.3103/S014641161903009X.

26. Lyon, A., Minchole´, A., Martı´nez, J. P., Laguna, P. & Rodriguez, B. "Computational techniques for ECG analysis and interpretation in light of their contribution to medical advances". *Journal of the Royal Society, Interface*. 2018; 15: 20170821. DOI: https://doi.org/10.1098/rsif.2017.0821

27. Biloborodova, T. O., Skarga-Bandurova, I. S. & Derevianchenko, V. S. "A wearable system for real-time outpatient ECG monitoring". *Visnik of the Volodymyr Dahl East Ukrainian National University*. 2019; 5 (253): 26–30. DOI: https://doi.org/10.33216/1998-7927-2019-253-5-26-30.

28. Schläpfer, J. & Wellens, H. J. "Computer-interpreted electrocardiograms: benefits and limitations". *Journal of the American College of Cardiology*. 2017; 70 (9): 1183–1192. DOI: https://doi.org/10.1016/j.jacc.2017.07.723.

29. Smulyan, H. "The computerized ECG: friend and foe". *The American Journal of Medicine*. 2019; Vol. 132 No. 2: 153–160. DOI: https://doi.org/10.1016/j.amjmed.2018.08.025.

30. Anoop, U. R., Ramesh, Verma, K. & Narayanan. "The ECG made easy for the dental practitioner". *Indian Journal of Dental Research*. 2014; 25 (3): 386–389. DOI: https://doi.org/10.4103/0970-9290.138349.

31. Filatova, A. E., Povoroznyuk, A. I. & Fahs, M. "Method of automatic determination of the heart's electrical axis in cardiological decision support systems". *Applied Aspects of Information Technology*. 2021; 4 (1): 11–23. DOI: https://doi.org/10.15276/aait.01.2021.1.

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Синтез інтегрального сигналу для вирішення проблеми морфологічного аналізу електрокардіограм

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АНОТАЦІЯ

Дана робота присвячена вирішенню науково-практичної проблеми морфологічного аналізу електрокардіограм на основі інтегрального біомедичного сигналу з локально-концентрованими ознаками. В сучасних умовах впровадження телемедицини в систему охорони здоров'я України особливого значення набуває створення кардіологічних систем підтримки прийняття рішень на основі автоматичного морфологічного аналізу ЕКГ. Авторами запропоновано методику синтезу інтегральної електрокардіограми у фронтальній площині від усіх відведень кінцівок з урахуванням кута відведення в гексаксіальній системі відліку та положення електричної осі серця, оскільки інтегральні електрокардіологічні сигнали дозволяють отримати більш точні результати в порівнянні зі звичайною ЕКГ, оскільки враховують індивідуальні особливості пацієнтів, велика різноманітність форм і комплексів ЕКГ, що пов'язано не тільки з наявністю патологічних процесів в міокарді, але і з положенням електричної осі серця, зокрема, на ЕКГ не буде реєструватися низькоамплітудний зубець P у II відведенні у разі горизонтального розташування електричної осі, але він буде чітко видно на інтегральному сигналі. Для реалізації запропонованого в статті методу була написана програма на мові MATLAB, висока швидкість обчислень і хороша оптимізація якої дозволяють отримувати результати набагато швидше і точніше, ніж при використанні традиційних підходів, а використання бібліотеки MATLAB Runtime, яка не вимагає ліцензування і поширюється безкоштовно, дозволило забезпечити більш економічну розробку, а також реалізувати взаємодію з популярними операційними системами, що робить її більш доступною і універсальною. Верифікацію результатів проводили за допомогою бази даних електрокардіограм, запис яких здійснювався за допомогою транстелефонного цифрового 12-канального електрокардіологічного комплексу «Телекард», що входить до складу лікувально-діагностичного комплексу «ТРЕДЕКС». Показано, що запропонований метод синтезу інтегрального сигналу з локально сконцентрованими ознаками дозволить підвищити якість морфологічного аналізу електрокардіограм у кардіологічних системах підтримки прийняття рішень.

Ключові слова: Морфологічний аналіз; біомедичні сигнали; локально зосереджені ознаки; інтегральна електрокардіограма; електрична вісь серця; кардіологічна система підтримки прийняття рішень

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