Mathematical, Algorithmic and Software Support for Phonocardiographic Signal Processing to Detect Mitral Insufficiency of Human Heart Valves

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Abstract

Mathematical support for phonocardiographic signal processing has been developed based on a mathematical model in the form of a periodically correlated stochastic process and a component processing method. On the basis of mathematical support, algorithmic and software was developed in the Matlab environment for automated systems of computer diagnostics of the functional state of the valves of the human heart when mitral insufficiency is detected.

Keywords

Mitral valve insufficiency of the human heart, phonocardiographic signal, mathematical support, periodically correlated stochastic process, component method, algorithmic support, software, Matlab.

1. Introduction

According to the WHO and the Medical Association of Cardiologists, it has been established that the development trend of human heart valve lesions occupies a dominant place among all cardiovascular diseases in Europe [1-19]. The primary causes of such lesions are congenital (arising during fetal development) and acquired (complications of rheumatism, infectious endocarditis or after surgical treatment of mitral stenosis) defects of the human heart.

In medical practice, such basic non-invasive instrumental research methods as cardiography [1,2], auscultation [17,18], echocardiography [4,6,13,14,15] and phonocardiography [17,19] are used to diagnose mitral insufficiency. Phonocardiography along with other methods makes it possible to objectify unclear sound phenomena of human heart valves (degree of weakening and presence of heart sounds, intensity, duration and form of systolic murmur) (Sacks, Roberts and Evans) according to registered phonocardiographic signals (PCG signals) (**Figure 1**).

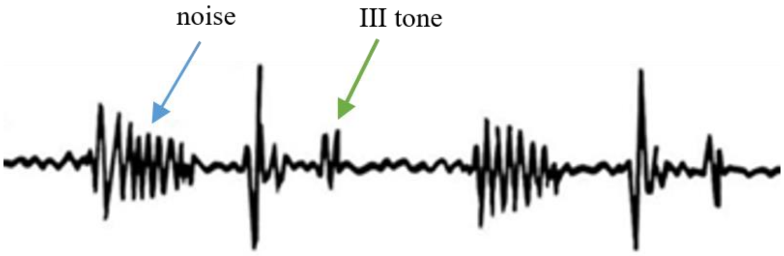

Figure 1: The structure of the PCG signal in mitral insufficiency: the I tone is weakened and merges with the noise of systole (indicated by the pointing arrow)

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Of particular value is the possibility of long-term (over a year or more) objective dynamic monitoring of the PCG signal during the formation of a valve defect. To implement the phonocardiography method in medical practice, hardware devices in the form of computer phonocardiographs are used, such as Cardio+ (Ukraine, Metekol LLC), PCG-02 (India, Mumbai), Techbook Scientech 2356 (India, Scientech Technologies Pvt . Ltd.) and Audio-Technica ATR288W (Japan). Well-known phonocardiographs based on the principle of obtaining diagnostic information about the condition of human heart valves are built according to the scheme "bioobject (human heart valves)-mathematical support (mathematical model-processing method)-algorithmic support-software-diagnosis result" [21,24,26,28,29,38,39,40]. In phonocardiographs, software and algorithmic support, which form the result of diagnostics, are implemented on the correlation, spectral and synphase methods of FCS processing, the core of which is a mathematical model in the form of a deterministic harmonic function (Dodge and Cabot), periodic functions of different frequencies (Manheimer), almost periodic functions (Kasyrskyi G.I.), a stationary stochastic process (Metin Akay (Houston)), a mixture of a stationary stochastic process and a deterministic function (Metin Akay (Houston)), periodically correlated stochastic process (Osukhivska H.M., Dragan Ya.P. [22,23,35,36], Palianytsia Y.B. [31,32]), relaxation multipulsator (Osukhivska H.M.) [37]. Such mathematical support (models and methods developed on their basis) of processing by its structure and properties does not provide tracking the temporal dynamics of changes in the amplitude and phase indicators of the functioning of the valves of the human heart, which is important in detecting the manifestations of mitral insufficiency over time.

Therefore, the development of mathematical support (a processing method based on its adequate mathematical model) and algorithmic-software processing of PCG signal for detecting mitral valve insufficiency of the human heart is an urgent scientific task.

2. Mathematical support for phonocardiographic signal processing

The experimentally recorded implementation of the PCG signal in the case of mitral insufficiency is shown in **Figure 2**.

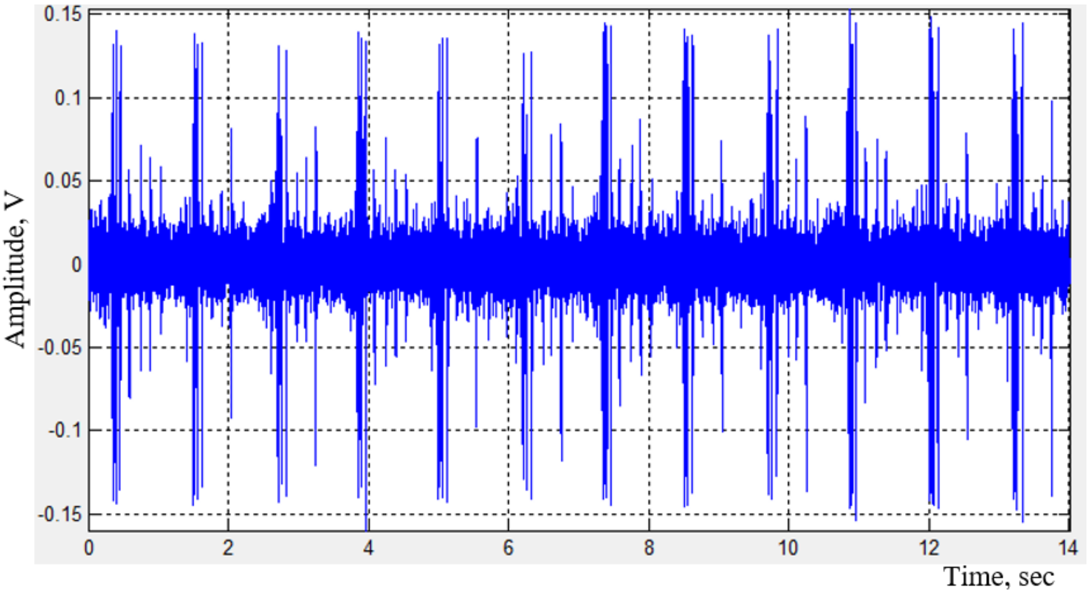


Figure 2: Experimentally recorded PCG signal (mitral regurgitation)

The PCG signal in mitral insufficiency as a stochastic and cyclical process by the nature of the correlation function satisfies the conditions of cyclicity of the average characteristics and their variations:

$$m(t+T)=m(t), \tag{1}$$

$$r(t+T,s+T)=r(t,s). \tag{2}$$

In this case, T corresponds to the duration of one PCG signal cycle in mitral insufficiency. Expressions (1-2) indicate the cyclic nature of the characteristics, namely that the values of the average characteristics and their variations due to the cardiac cycle are repeated, but with changes caused by chance.

PCG signal in the case of mitral class insufficiency provides the study of its type of harmonicity as a process of stochastic and cyclic nature in the form of PCSP from the standpoint of the energy approach (developer Ya.P. Dragan [20,22,23,30,31,32,33,34]).

Since the PCG signal in mitral insufficiency is presented in a stochastic process with cyclic characters of a finite nature, it can be represented through the expression of translational components [20]:

$$\xi(t)=\sum_{p\in Z}\sum_{k\in Z}H(t-pT)\xi_k(t)+q(t), \tag{3}$$

where is a $H(\bullet)$ single function that indicates the place of generation of the PCG signal tone in mitral insufficiency; T - is the cycle period of the PCG signal in case of mitral insufficiency; $\xi_k(t)$ - PCG signal tones in case of mitral insufficiency within the cardiac cycle; k - cardiac cycle number.

But based on the equivalence of representations through translational components (3) and stationary components, the expression of the PCG signal model in mitral insufficiency has the form [20-23,28,31,32]:

$$\xi(t)=\sum_{k\in Z}\xi_k(t)e^{ik\frac{2\pi}{T}t},\ t\in \mathrm{R} \tag{4}$$

where are $\xi_k(t)$ the steady-state components of the PCG signal in mitral insufficiency.

Mitral insufficiency by nature has the appearance of a noise similar in shape to white noise. Such similarity should be reflected in model (4) additively in the form of an expression:

$$\xi(t)=\sum_{k\in Z}\xi_k(t)e^{ik\frac{2\pi}{T}t}+n(t),\ t\in \mathrm{R} \tag{5}$$

where $n(t)$ is white noise as a sign of mitral insufficiency in the realization of the PCG signal (according to the nature of its formation).

Expression (5) ensures the use of the component method for the processing of the PCG signal in the case of mitral insufficiency as a stochastic process with cyclic characters of a finite nature.

The component method of PCG signal processing based on model (5) ensures the calculation of correlation components according to the expression [20,24,27,28]:

$$\hat{B}_k(u)=\frac{1}{T}\int_0^T\overset{0}{\xi}(t+u+kT)\overset{0}{\xi}(t+kT)e^{-ik\frac{2\pi}{T}t}dt,\ t\in \mathrm{R} \tag{6}$$

where is $\overset{0}{\xi}(t)=\overset{0}{\xi}(t)-m_\xi(t)$ a centered PCG signal with mitral valve insufficiency; $m_\xi(t)$ - the average PCG signal in the case of mitral valve insufficiency.

3. Algorithmic support for phonocardiographic signal processing

Having considered the expression (6), the main operations of its implementation are highlighted:

1. Finding the T period of the FCG signal in the case of mitral valve insufficiency [25].
2. Calculation of the estimate of the mathematical expectation m_ξ of the PCG signal in the case of mitral valve insufficiency.
3. Centering of the PCG signal in the case of mitral valve insufficiency $\overset{0}{\xi}(t)$.
4. Calculation of the covariance $\overset{0}{\xi}(t+u+kT)\overset{0}{\xi}(t+kT)$ of the PCG signal in the case of mitral valve insufficiency.
5. Counting the components $\hat{B}_k(u)$ of the PCG signal in case of mitral valve insufficiency.

In **Figure 3**, we show all the listed operations in the form of an algorithm, which displays all the operations of implementing the component method of processing.

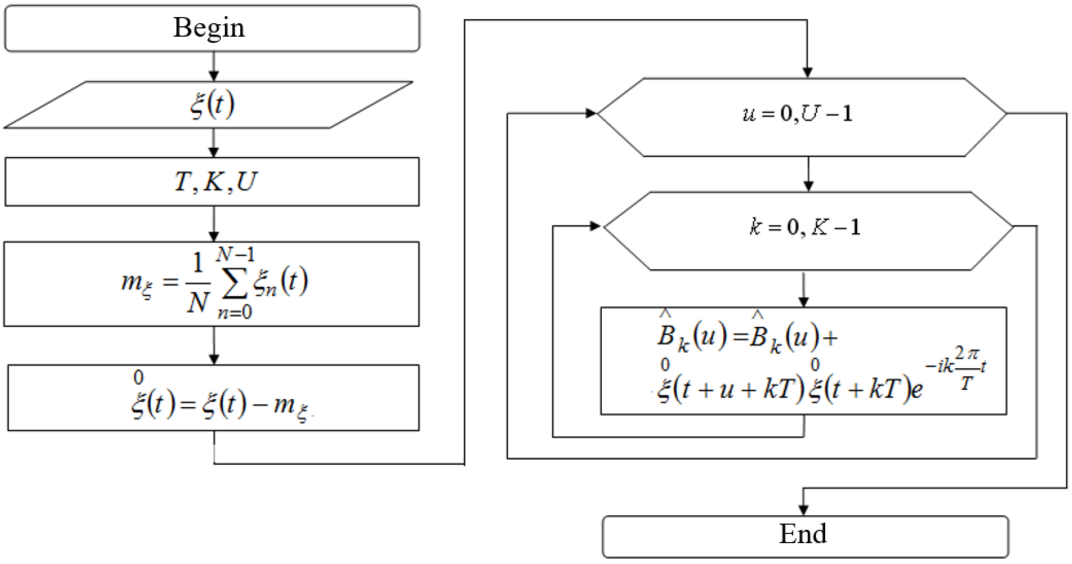


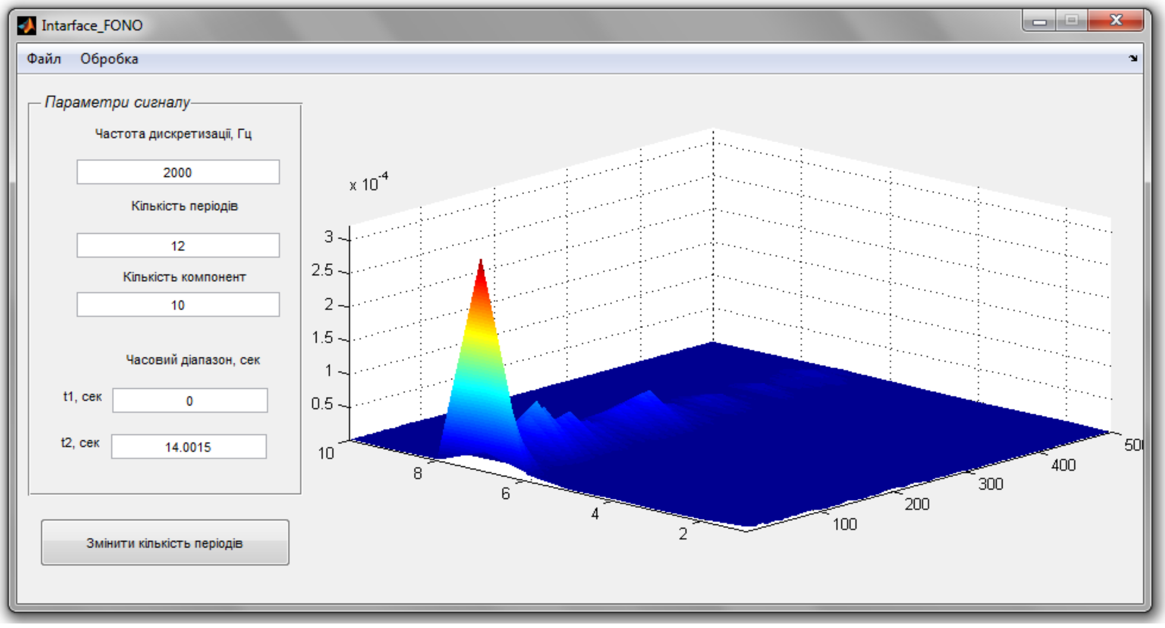
Figure 3: Algorithm of component processing of PCG signal in case of mitral valve insufficiency

Figure 3 shows K the number of components, U the maximum length of the time shift, and T the duration of the heart cycle.

4. Software and results of phonocardiographic signal processing

Software with a graphical user interface was developed in the MATLAB environment to automate the process of processing the PCG signal when mitral insufficiency is detected.

The results of processing PCG signals in the normal state (Patient A) and in the presence of mitral insufficiency (Patient B) are shown in **Figure 4-7**.



Параметри сигналу

Частота дискретизації, Гц: 2000

Кількість періодів: 12

Кількість компонент: 10

Часовий діапазон, сек

t1, сек: 0

t2, сек: 14.0015

Figure 4: Realization of correlated (spectral) components of the PCG signal (Patient A - norm) (axis X – number of components, Y – shift, Z – power)

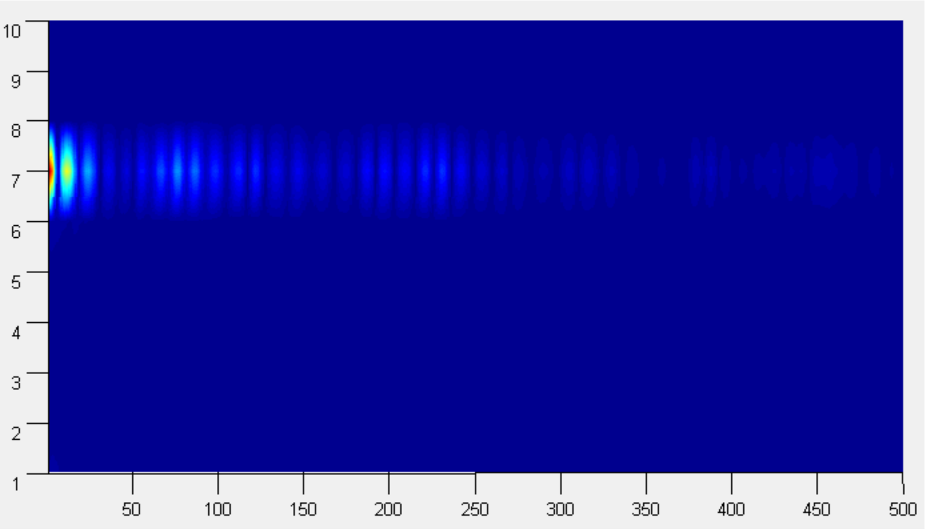
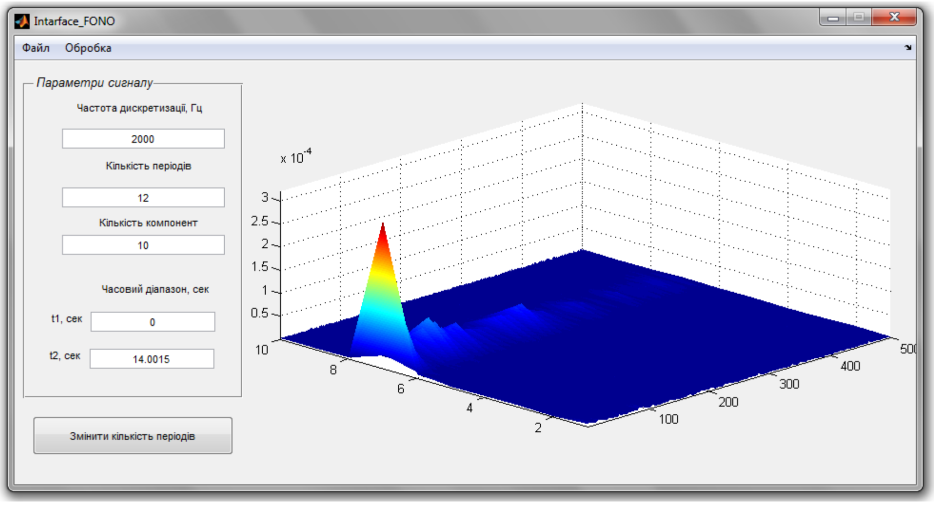


Figure 5: Realization of the components of the PCG signal (Patient A - norm) (axis X – component number, Y – offset) (top view)



Параметри сигналу

Частота дискретизації, Гц: 2000

Кількість періодів: 12

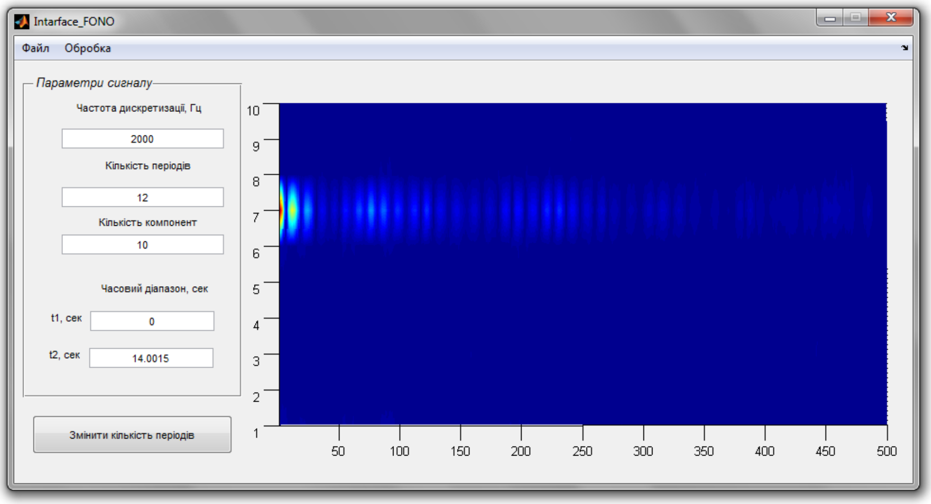
Кількість компонент: 10

Часовий діапазон, сек

t1, сек: 0

t2, сек: 14.0015

Figure 6: Realization of correlated (spectral) components of the PCG signal (Patient B - mitral valve insufficiency) (axis X – number of components, Y – shift, Z – power, V^2)



Параметри сигналу

Частота дискретизації, Гц: 2000

Кількість періодів: 12

Кількість компонент: 10

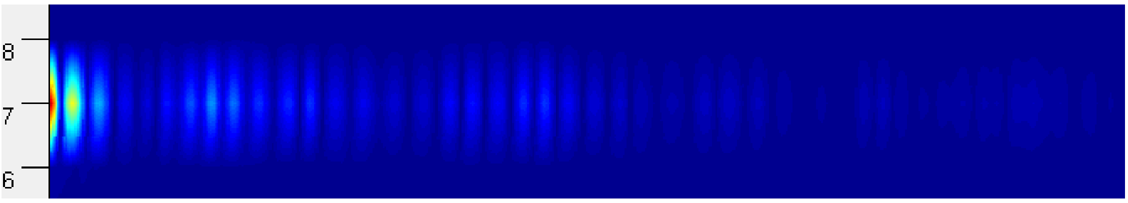
Часовий діапазон, сек

t1, сек: 0

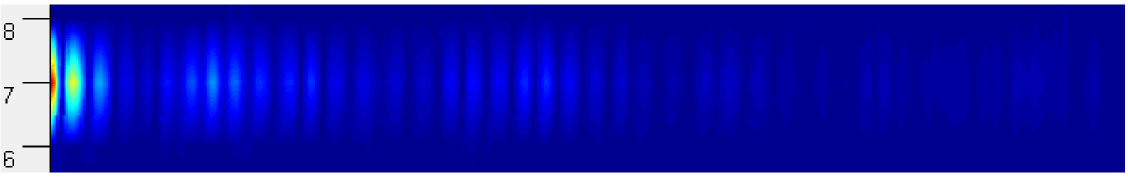
t2, сек: 14.0015

Figure 7: Realization of correlated (spectral) components of the PCG signal (Patient B - mitral valve insufficiency) (X axis – component number, Y – shift) (top view)

A comparison of the magnified view of the components from above is shown in **Figure 8**.



(Patient A - norm)

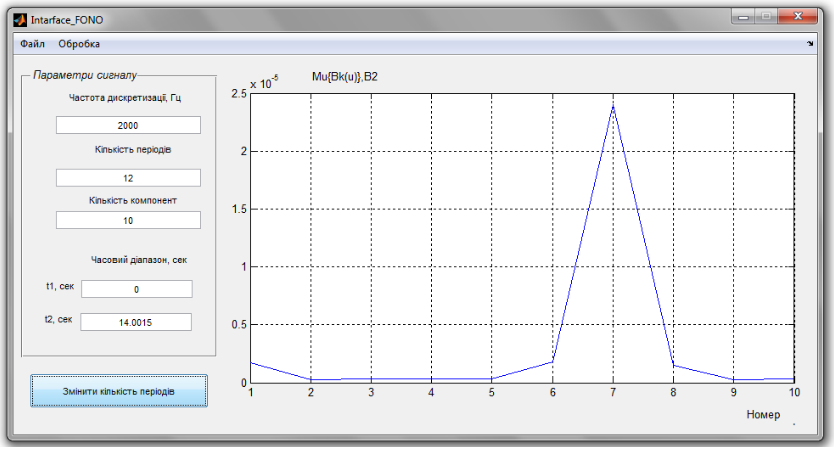


(Patient B - mitral insufficiency)

Figure 8: Magnified samples of correlation (spectral) components of the PCG signal (top view)

According to the results of the analysis of the correlation components, a slight change in the power intensity of the components is visible, namely, with mitral insufficiency, the power is more scattered than in the normal state. The components allow only visual detection of changes in the operation of human heart valves without quantitative evaluation.

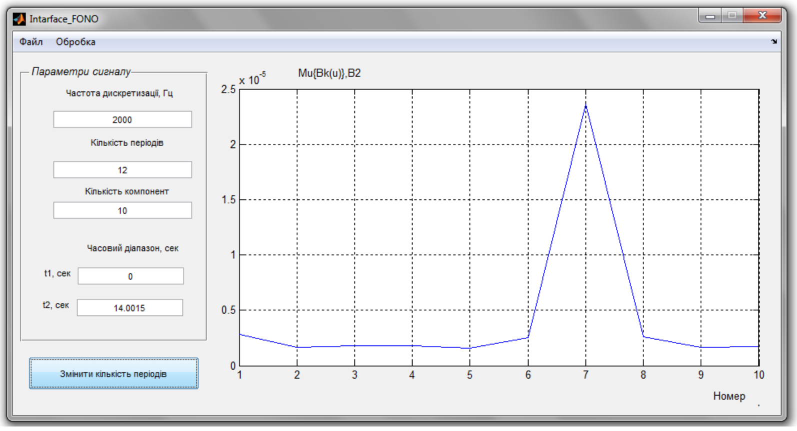
For the quantitative evaluation of correlation (spectral) components, the evaluation of their averaging by time shifts was used (**Figure 9-10**).



Параметри сигналу

Частота дискретизації, Гц: 2000
Кількість періодів: 12
Кількість компонент: 10
Часовий діапазон, сек
t1, сек: 0
t2, сек: 14.0015

Figure 9: Realization of the averaged components of the PCG signal (Patient A - norm)



Параметри сигналу

Частота дискретизації, Гц: 2000
Кількість періодів: 12
Кількість компонент: 10
Часовий діапазон, сек
t1, сек: 0
t2, сек: 14.0015

Figure 10: Implementation of the averaged spectral components of the PCG signal (Patient B - mitral valve insufficiency)

In **Figure 9-10** it is visually and quantitatively visible that the maximum values of the averaged components for a patient in a physiologically normal state (patient A) and a patient with mitral valve insufficiency (patient B) are concentrated at the same frequencies (identical in structure), but the amplitude values of the estimates slightly differ from each other, namely, for patients A and B, the maximum amplitudes are concentrated on the 1st and 7th components. However, an increased power level of the 2nd, 3rd, 4th, and 5th components, as well as an increase in the maximums of the 1st and 7th components, were noticed in patient B. Such changes quantitatively reflect the manifestations of mitral valve insufficiency of the human heart.

Therefore, the calculation of correlation (spectral) components is a quantitative parameter for detecting early changes in the functioning of the valves of the human heart, in particular valve insufficiency.

5. Conclusions

The work substantiates the mathematical model of the PCG signal as a mixture of a periodically correlated stochastic process and noise for solving the problem of detecting the insufficiency of the mitral valves of the human heart. A method and algorithm for processing the PCG signal based on the component method was developed, which provided a procedure for detecting the insufficiency of the mitral valves of the human heart based on the averaged estimates of the correlation components. Software was developed using the MATLAB tool for processing the empirical data of the PCG signal, which provided the process of calculating correlation components as diagnostic signs that quantitatively reflect indicators of mitral valve insufficiency of the human heart.

6. References

[1] Baumgartner H, Falk V, Bax JJ, De Bonis M, Hamm C, Holm JP, et al. ESC/EACTS Guidelines for the management of valvular heart disease. Eur Heart J. 2017;38(36): 2739–2791. Available from: doi: 10.1093/eurheartj/ehx391.

[2] Dal-Bianco JP, Aikawa E, Bischoff J, et al. Myocardial infarction alters adaptation of the tethered mitral valve. J Am Coll Cardiol. 2016; 67(3): 275–287. doi:10.1016/j.jacc.2015.10.092.

[3] Deferm S, Bertrand PB, Verbrugge FH, et al. Atrial functional mitral regurgitation: JACC review topic of the week. J Am Coll Cardiol. 2019;73(19):2465–2476. doi:10.1016/j.jacc.2019.02.061.

[4] Deferm S, Bertrand PB, Verhaert D, et al. Mitral annular dynamics in AF versus sinus rhythm: Novel insights into the mechanism of AFMR. JACC Cardiovasc Imaging. 2021;S1936–878X(21)00440-X. doi:10.1016/j. jcmg.2021.05.019.

[5] Donal, E; Panis, V (October 2021). "Interaction between mitral valve apparatus and left ventricle. Functional mitral regurgitation: A brief state-of-the-art overview". Advances in Clinical and Experimental Medicine. 30 (10): 991–997. doi:10.17219/acem/143324. PMID 34714608. S2CID 240154628.

[6] Gertz ZM, Raina A, Saghy L, et al. Evidence of atrial functional mitral regurgitation due to atrial fibrillation: Reversal with arrhythmia control. J Am Coll Cardiol. 2011;58(14):1474–1481. doi:10.1016/j.jacc.2011.06.032.

[7] Grayburn PA, Sannino A, Packer M. Proportionate and disproportionate functional mitral regurgitation: A new conceptual framework that reconciles the results of the MITRA-FR and COAPT trials. JACC Cardiovasc Imaging. 2019;12(2):353–362. doi:10.1016/j.jcmg.2018.11.006.

[8] Eng MH, Wang DD. Transseptal transcatheter mitral valve replacement for post- surgical mitral failures. Intervent Cardiol Rev. 2018;13(2): 77–80. Available from: doi: 10.15420/icr.2017:16:3.

[9] Iung B, Baron G, Butchartv EG, Delahaye F, Gohlke-Baerwolf CW, Leavang OW, et al. A prospective survey of patients with valvular heart disease in Europe: The Euro Heart Survey on Valvular Heart Disease. Eur Heart J. 2003;24: 1231– 1243. Available from: doi: 10.1016/50195-668X(03)00201-X.

[10] Kang DH, Park SJ, Shin SH, et al. Angiotensin receptor neprilysin inhibitor for functional mitral regurgitation. Circulation. 2019;139(11):1354–1365. doi:10.1161/CIRCULATIONAHA.118.037077.

[11] Levine RA, Hagege AA, Judge DP, et al. Mitral valve disease: Morphology and mechanisms. Nat Rev Cardiol. 2015;12(12):689–710. doi:10.1038/nrcardio.2015.161.

[12] Madesis A, Tsakiridis K, Zarogoulidis P, Katsikogiannis N, Machairiotis N, Kougioumtzi I, et al. Review of mitral valve insufficiency: repair or replacement. J Thorac Dis. 2014;6(1): 39–51. Available from: doi: 10.3978/j.issn.2072- 1439.2013.10.20.

[13] Melillo E, Ancona F, Buzzatti N, Denti P, Agricola E. A challenging mitral valve anatomy for percutaneous repair with MitraClip: Cleft posterior leaflet. Eur Heart J Cardiovasc Imaging. 2019;20(12):1433–1434. doi:10.1093/ehjci/jez175.

[14] Marsit O, Clavel MA, Cote-Laroche C, et al. Attenuated mitral leaflet enlargement contributes to functional mitral regurgitation after myocardial infarction. J Am Coll Cardiol. 2020;75(4):395–405. doi:10.1016/j.jacc.2019.11.039.

[15] Sweeney J, Dutta T, Sharma M, et al. Variations in mitral valve leaflet and scallop anatomy on 3-dimensional transesophageal echocardiography. J Am Soc Echocardiogr. 2021;S0894–7317(21)00598-8. doi:10.1016/j.echo.2021.07.010.

[16] Stone GW, Lindenfeld J, Abraham WT, et al. Transcatheter mitral-valve repair in patients with heart failure. N Engl J Med. 2018;379(24):2307–2318. doi:10.1056/NEJMoa1806640.

[17] Gianelly, R. E., Popp, R. L. and Hultgren, H. N. (1970). Heart sounds in patients with homograft replacement of the mitral valve. Circulation, 42, 309.

[18] Lim, Eric; Ali, Ziad A; Barlow, Clifford W; Hosseinpour, A Reza; Wisbey, Christopher; Charman, Susan C; Wells, Francis C; Barlow, John B; (2002) Determinants and assessment of regurgitation after mitral valve repair. The Journal of thoracic and cardiovascular surgery, 124 (5). pp. 911-917. ISSN 0022-5223 DOI: https://doi.org/10.1067/mtc.2002.125341.

[19] Jun Heum Yon, Song Ook Han, Yun Hee Lim, Kye Min Kim, Youn Suk Lee, Ki Hyuk Hong. (2000). Experience of Phonocardiogram during the Mitral Valve Replacement. Korean Journal of Anesthesiology. 39(2):275-277. DOI: https://doi.org/10.4097/kjae.2000.39.2.275

[20] Dragan Ya.P. Enerhetychna teoriia liniinykh modelei stokhastychnykh syhnaliv. Lviv: Tsentr stratehichnykh doslidzhen eko- bio- tekhnichnykh system, 1997. 361p. [in Ukrainian].

[21] V. Martsenyuk, A. Sverstiuk, A. Klos-Witkowska, A. Horkunenko, S. Rajba, Vector of diagnostic features in the form of decomposition coefficients of statistical estimates using a cyclic random process model of cardiosignal. Proceedings of the 2019 10th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, IDAACS 2019, 1, pp. 298–303. doi: 10.1109/IDAACS.2019.8924398.

[22] Dragan Yaroslav P., Osukhivskaya G.M. Description of sound cardiosignals by periodically correlated random process model. Journal of Automation and Information Sciences. Volume 31, Issue 7-9, 1999, pp. 59-63. doi: 10.1615/JAutomatInfScien.v31.i7-9.100. ISSN: 10642315.

[23] Dragan Ya. P., Osukhivska H. M. Invarianty tonalnoho syhnalu na pidstavi yoho modeli u vyhliadi periodychno korelovanoho vypadkovoho protsesu // Visnyk Derzhavnoho universytetu “Lvivska politekhnika”. Lviv vyd-vo Derzh. un-tu “Lvivska politekhnika”. 1998. Vol.1, №337. P. 164-166. [in Ukrainian].

[24] Dunets V.L., Khvostivskyi M.O., Sverstiuk A.S., Khvostivska L.V. Matematychne ta alhorytmichno-prohramne zabezpechennia opratsiuvannia elektrokadiosyhnaliv pry fizychnomu navantazhenni u kardiodiahnostychnykh systemakh: naukova monohrafiia. Lviv: Vydavnytstvo «Mahnoliia - 2006», 2022. 136 p. [in Ukrainian].

[25] Hvostivska L.V., Osukhivska H.M., Hvostivskyy M.O., Shadrina H.M., Dediv I.Yu. Development of methods and algorithms for a stochastic biomedical signal period calculation in medical computer diagnostic systems. Visnyk NTUU KPI Seriia - Radiotekhnika Radioaparatobuduvannia, (79), pp. 78-84. doi: 10.20535/RADAP.2019.79.78-84.

[26] Franchevska H., Khvostivskyi M., Dozorskyi V., Yavorska E., Zastavnyy O. The Method and Algorithm for Detecting the Fetal ECG Signal in the Presence of Interference. Proceedings of the 1st International Workshop on Computer Information Technologies in Industry 4.0 (CITI 2023). CEUR Workshop Proceedings. Ternopil, Ukraine, June 14-16, 2023. P.263-272. ISSN 1613-0073.

[27] Hvostivska L., Hvostivskyy M. (2017) Veryfikatsiia synfaznoho ta komponentnoho metodiv analizu pulsovoho syhnalu. Materials of XX Conference TNTU I. Puluj (Tern., 17-18 May 2017), pp. 137-138 [in Ukrainian].

[28] Khvostivska L.V. Mathematical model and methods of pulse signal analysis to increase the informativeness of photoplethysmographic systems: dissertation for obtaining the scientific degree of candidate of technical sciences by specialty 05.01.02 / Liliya Volodymyrivna Khvostivska. Ternopil: TNTU, 2021. 177 p.

[29] Khvostivska L., Uniyat S., Khvostivskyi M., Yavorskyi I. Mathematical Support Verification of Methods, Algorithms and Software Processing of Pulse Signals under Physical Load in Computer Diagnostic Systems. Proceedings of the XXVIII International Scientific and Practical Conference. Melbourne, Australia. 2023. Pp. 185-190. ISBN 979-8-89074-574-3. DOI: 10.46299/ISG.2023.1.28.

[30] Khvostivska L., Khvostivskyi M., Dediv I., Yatskiv V., Palaniza Y. Method, Algorithm and Computer Tool for Synphase Detection of Radio Signals in Telecommunication Networks with Noises. Proceedings of the 1st International Workshop on Computer Information Technologies in Industry 4.0 (CITI 2023). CEUR Workshop Proceedings. Ternopil, Ukraine, June 14-16, 2023. P.173-180. ISSN 1613-0073.

[31] Palianytsia Yu. B. Suchasni pidkhody do opratsiuvannia fonokardiosyhnalu ta matematychna model yoho u vyhliadi periodychno korelovanoho vypadkovoho protsesu // Visnyk Khmelnytskoho natsionalnoho universytetu. Tekhnichni nauky, 2016. Vyp. 2(235). S. 90–93. [in Ukrainian].

[32] Palaniza Y., Yavorska E., Shadrina H., Dediv L. (2018) Phonocardiosignal as a periodically correlated stochastic process preprocessing algorithm structure grounding. Scientific Journal of TNTU (Tern.), vol. 91, no 3, pp. 143-152.

[33] Palaniza Y.B., Shadrina H.M., Khvostivskiy M.O., Dediv L.Ye., Dozorska O.F. Main theoretical basis of biosignals modeling. Znanstvena misel. Slovenia. 2018. №16. P. 39-44Wang, Xin, Tapani Ahonen, and Jari Nurmi. "Applying CDMA technique to network-on-chip." IEEE transactions on very large scale integration (VLSI) systems 15.10 (2007): 1091-1100.

[34] Palaniza Y., Franchevska H. (2018) Enerhetychni aspekty obrobky biosyhnaliv u kardiolohichnii praktytsi [Energy aspects of biosignals processing in cardiology practice]. Book of abstract of the VII International scientific and technical conference of young researchers and students "Current issues in modern technologies" (Tern., 28-29 November 2018), vol. 3, pp. 243 [in Ukrainian].

[35] Osukhivska H. M. Matematychna model tonovoho syhnalu dlia diahnostyky stanu klapaniv sertsia liudyny: avtoref. dys. na zdobuttia nauk, stupenia kand. tekhn. nauk: 01.05.02 / H.M. Osukhivska. Ternopil, 1999. 20 p. [in Ukrainian].

[36] H. Osuhivs'ka and I. Kyslak, "Random processes statistic application for cardiosignals characteristics determination," MMET '96. VIth International Conference on Mathematical Methods in Electromagnetic Theory. Proceedings, Lviv, Ukraine, 1996, pp. 264-266, doi: 10.1109/MMET.1996.565708.

[37] Osukhivska H. M. Matematychna model porodzhennia tonovoho syhnalu u vyhliadi relaksatsiinoho multypulsatora. Materialy 6-oi nauk. konf. TDTU imeni Ivana Puliuia. Ternopil: TDTU. 2002. P.9. [in Ukrainian].

[38] Khvostivska L., Khvostivskyy M., Dunetc V., Dediv I. Mathematical and Algorithmic Support of Detection Useful Radiosignals in Telecommunication Networks. Proceedings of the 2nd International Workshop on Information Technologies: Theoretical and Applied Problems (ITTAP 2022). Ternopil, Ukraine, November 22-24, 2022. P.314-318. ISSN 1613-0073.

[39] I. V. Lytvynenko; P. O. Maruschak; S. A. Lupenko; Yu. I. Hats; A. Menou; S. V. Panin Software for segmentation, statistical analysis and modeling of surface ordered structures, AIP Conf. Proc. 1785, 030012, 2016, https://doi.org/10.1063/1.4967033.

[40] S. Lupenko, I. Lytvynenko, A. Sverstiuk, A. Horkunenko, B. Shelestovskyi, Software for statistical processing and modeling of a set of synchronously registered cardio signals of different physical nature. CEUR Workshop Proceedings, 2021, 2864, pp. 194-205.