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## MODELING THE PROCESS OF RECOGNITION OF PACEMAKER DYSFUNCTION

*The article presents a comprehensive study aimed at solving a pressing scientific and practical problem - modeling and designing information technology for recognizing pacemaker dysfunctions to increase the efficiency of diagnostics and reliability of life support systems. The relevance of the work is due to the rapid growth of the number of cardiovascular diseases in the world and in Ukraine in particular, which leads to an increase in the number of operations for implanting pacemakers, the functioning of which requires continuous and high-precision monitoring. The authors analyzed the world experience in using modern diagnostic tools, including neural networks for analyzing radiographs, mobile applications for remote monitoring, and machine learning algorithms for ECG analysis, which revealed the lack of integrated solutions that would combine different methods for detecting technical and clinical failures. The proposed approach is based on the use of multimodal input data, such as information about the patient's symptoms (dizziness, arrhythmia, weakness), device hardware reports (pacing rate, battery status, intracardiac signals), ECG and Holter monitoring results, as well as data from physical activity and intracardiac pressure sensors. The scientific novelty of the study lies in the development of a mathematical model of the process of recognizing pacemaker dysfunction, presented as a sequence of tuples and transformations that provide data preparation, selection of the most informative signs of cardiac activity and direct recognition of the system state. Special attention is paid to the stages of signal normalization and artifact filtering, which guarantees high accuracy of classification of disorders even under difficult operating conditions or during physical exertion of the patient. The practical significance of the work is confirmed by the creation of a structure of output results, which include not only automated fixation of anomalies, but also the formation of specific recommendations for changing pacemaker settings and instant notification of medical personnel, relatives and the patient himself. The proposed technology allows to ensure a continuous monitoring cycle, minimize the risk of human error when interpreting complex diagnostic data and significantly improve the prognosis for patients with high dependence on an artificial pacemaker. Thus, the results obtained create a reliable foundation for building modern information technologies for cardiac care.*

*Keywords: cardiovascular diseases, pacemaker, pacemaker dysfunction, information technology, cardiac monitoring, electrocardiography, anomaly recognition, mathematical modeling, diagnostic data processing, decision support, automated informing, sensory integration.*

### Introduction

Cardiovascular diseases, such as coronary heart disease and stroke, are the leading causes of death and one of the leading causes of disability worldwide in the twenty-first century [1].

Over the decades, the burden of cardiovascular disease has continued to increase in almost all middle- and low-income countries [1]. It is also worth noting that the age-standardized rate of cardiovascular disease has begun to increase in some high-income countries, where there had previously been a decline. This is confirmed by numerous studies and statistical data from various monitoring companies. The number of cases of cardiovascular disease has almost doubled from 271 million in 1990 to 523 million in 2019, and the number of deaths from these diseases has also increased, from 12.1 million in 1990 to 18.6 million in 2019. In Ukraine as a whole, mortality from cardiovascular diseases has increased by almost 8% over the past 29 years, reaching 449,376 in 2019 and accounting for 64.3% of the total number of deaths. In 1990, this figure was 350,605 deaths, or 56.5% [1]. With the development of medicine, the possibilities of influencing the work of the heart have expanded significantly. Today, electronic

devices, known as pacemakers, play a critically important role in preserving the health and lives of patients with heart rhythm disorders. Thanks to these devices, millions of people around the world can lead full lives despite heart problems [2-4].

Pacemakers are special implanted electronic devices that monitor the electrical activity of the heart and, if necessary, send electrical impulses to stimulate heart contractions. They are used in cases where the patient develops arrhythmias – heart rhythm disturbances, such as bradycardia or heart conduction system blocks. The main function of these medical devices is to ensure a stable heart rhythm and restore the correctness of heart contractions if the natural heart rhythm is disturbed for people who have abnormalities or disorders of cardiac activity [5]. Pacemakers are not just a technological device, but a real support for the heart, allowing patients not only to survive, but also to return to a normal, active life [2, 4]. Thanks to them, many patients can avoid serious consequences, such as strokes, cardiac arrest or sudden death. In addition, modern devices are equipped with self-diagnosis functions and data transmission to the doctor remotely, which allows you to effectively monitor the patient's condition and respond to changes in a timely manner.

A typical pacemaker consists of an implanted pulse generator placed under the skin, usually in the chest area, and one or more electrodes that connect the device to the heart muscle. Modern models have the ability to adapt to the patient's physical activity, changing the stimulation frequency according to the body's needs [6].

The need for pacemakers is constantly growing. About 1 million such devices are installed worldwide every year, and this figure continues to grow. They have become an integral part of modern cardiology and save the lives of hundreds of thousands of patients every year [7-9].

A pacemaker is a vital device for certain categories of patients with cardiovascular pathologies, in particular with heart rhythm disorders. Its main function is to maintain the proper frequency and sequence of heart contractions by delivering electrical impulses to the myocardium. The correct operation of a pacemaker is extremely important, since not only the quality of life, but also the threat to the patient's life directly depends on it. Any malfunction of the device can lead to significant deterioration of health or even have fatal consequences [10-12].

Any deviations in the operation of a pacemaker are a serious medical problem that requires urgent diagnosis and intervention by qualified specialists. Regular monitoring, monitoring of device parameters, as well as compliance with recommendations for the patient's lifestyle and regimen are key factors in ensuring the effective functioning of the pacemaker and preventing complications.

To ensure reliable and safe operation of a pacemaker, regular maintenance is necessary, monitoring of operating parameters, patient compliance with doctor's recommendations, and software updates as needed. The reliability of such a device largely depends on both the quality of its engineering design and the patient's conscious handling of the device.

Recognition of pacemaker dysfunction is a complex process that combines clinical observations, technical monitoring, signal analysis, and the use of specialized algorithms.

A pacemaker malfunction can be recognized by certain characteristic parameters or patterns of device behavior. Detection of such changes allows for timely intervention and prevention of negative consequences. An important role in this is played by software, which must have modules for automatic signal analysis, statistics collection, assessment of change trends, and the ability to respond to potentially dangerous situations.

The list of possible parameters that may indicate the onset or presence of dysfunction [12, 13]:

- 1) battery status – monitoring the pacemaker battery level allows for advance warning of the need to replace the device or its components;
- 2) cardiac activity signals – electrocardiographic indicators recorded by the device allow for the detection of deviations in the rhythm or effectiveness of stimulation;
- 3) diagnostic messages – the presence of system messages or error codes helps to accurately localize the problem, saving resources and time for doctors and patients;
- 4) electrode status – contact disruption or electrode displacement can affect the efficiency of impulse transmission to the heart muscle, which in turn can be monitored using a pacemaker status monitoring system;
- 5) device performance metrics – failures in the frequency or amplitude of stimulation, changes in the time intervals between pulses can indicate deviations in functioning;
- 6) user reports – patient complaints of symptoms that may be related to an irregular heart rhythm, such as dizziness, fainting, chest pain, etc. – require immediate and thorough device inspection;
- 7) software information – update data, parameter configuration, logs, and event schedules can indicate potential technical problems;
- 8) history tracking – analysis of previous failure cases allows for more effective algorithms to predict and prevent similar situations in the future.

Since pacemakers have been used for a relatively long time, and all this time, research and development of methods for maintaining the pacemaker in proper condition, algorithms for checking the validity of the received data, checking for any breakdowns or failures, etc., are being conducted in parallel, because the patient's life depends on it.

The current state of scientific research in the field of pacemakers indicates the active implementation of artificial intelligence methods to automate complex diagnostic processes. In particular, the use of deep convolutional neural networks allows for high-precision identification of device types on radiographs, which is critically important

for safe MRI [14]. Such networks automatically classify models according to their visual characteristics, minimizing the human factor. At the same time, machine learning algorithms ensure the detection of technical failures even in the absence of data about a specific model or its interface [15], which makes them indispensable for emergency medicine, where the time for diagnosis is limited.

Automatic ECG analysis based on deep learning is currently considered one of the most promising methods for early prevention of cardiac abnormalities and pacemaker dysfunction [16]. These systems are able to recognize subtle changes in electrical signals that may precede critical device failure. This significantly expands diagnostic capabilities compared to traditional visual analysis methods, allowing doctors to act in advance. The introduction of such analytical tools into clinical practice can significantly reduce the risk of sudden complications in patients with high dependence on stimulation.

Considerable attention is paid by researchers to the problem of misinterpretation of the operation of modern devices, whose complex stimulation algorithms can simulate malfunctions. Reviews of clinical cases [17-19] demonstrate that functional features or specific modes, such as automatic mode switching or hysteresis algorithms, are often perceived as device failure. This leads to unnecessary expenditure of medical resources and causes significant anxiety in patients. The authors emphasize that careful analysis is necessary before making a decision to replace the device, since what appears to be a defect is often the planned operation of the algorithm.

Of particular note are cases where specific cardiac surgical interventions affect the heart rhythm, masking the pacemaker. For example, after transcatheter aortic valve implantation (TAVR), a junctional rhythm may occur that mimics pacemaker failure [20]. This emphasizes the need for careful differential analysis and consideration of the patient's clinical situation to avoid misdiagnosis. Understanding the mechanisms of such rhythms allows physicians to accurately determine the cause of the disorders and provide appropriate treatment without unnecessary surgical revisions of the pacemaker site.

In parallel with analytical methods, innovative mobile monitoring systems are being developed that allow monitoring the patient's condition in dynamics outside the hospital. Mobile applications, such as HeartSync for iPhone, provide continuous comparison of pacemaker data at different time intervals to quickly detect functional degradation [21]. The results of such monitoring are transmitted directly to doctors, creating a closed loop of control. This allows detecting malfunctions at early stages, when they have not yet led to a deterioration in the patient's well-being, providing a new level of personalized medicine.

An additional tool for assessing the state of the cardiovascular system in patients with implants is acoustic heart rate monitoring. A study [22] suggests using mobile systems to assess left ventricular systolic function, which is important for detecting the progression of heart failure. Since pacemaker dysfunction often correlates with hemodynamic deterioration, such acoustic tools become an auxiliary marker of hidden technical problems. This integrated observation of the mechanical function of the heart and the electrical activity of the device allows for a more complete clinical picture.

Computer modeling is now being actively used to improve software and create new therapy algorithms. The use of virtual models of the heart allows for the simulation of the interaction of the organ with the pacemaker in a safe digital environment [23]. This allows developers to test new software and improve electrophysiology methods without risk to patients. In addition, specialized systems for testing parameters [24] help to detect hidden malfunctions in electronic components that are difficult to diagnose using standard clinical methods.

An important aspect of safe operation is to minimize the impact of external factors, in particular electromagnetic radiation. The study [25] emphasizes that modern pacemakers remain sensitive to external fields that can provoke errors in the software cycle. This requires increased vigilance from doctors and patients in the conditions of the modern technogenic environment. Proper adjustment of the device's filters and protection mechanisms is critical to ensure stable operation in the face of potential interference, and should also be part of the overall monitoring strategy.

Clinical practice confirms that ignoring or delaying the detection of malfunctions can have fatal consequences. Article [26] describes in detail a case where a late-detected dysfunction led to serious complications, highlighting the vital importance of regular monitoring. Similarly, [27] discusses a case of complete device failure during a medical examination, where only prompt differential diagnosis between arrhythmia and device failure allowed the patient to be stabilized. These cases emphasize the need for tools that can automatically rank diagnoses by probability.

Comprehensive reviews of problems in emergency medicine [28-30] conclude that technological developments increase the reliability of devices, but require medical personnel to have a deep knowledge of possible types of failures, such as electrode displacement or lack of pulse capture. The need to combine physical examination, ECG monitoring and remote data transmission is a key thesis of modern protocols. However, the analysis of the literature shows that existing tools operate in a disparate manner. This determines the relevance of developing a new information technology that would synthesize all available methods to create a single, most reliable diagnostic environment. Therefore, the purpose of this study is to model the process of recognizing pacemaker dysfunction, which will become the theoretical basis for the future information technology for recognizing pacemaker dysfunction.

### Functional modeling of information technology for recognizing the pacemaker dysfunction

Functional modeling is an important stage in the process of creating an information technology for recognizing pacemaker dysfunction, as it allows you to determine the composition, structure, functions and relationships of the system components. This approach allows you to systematically form the requirements for the technology, ensure its compliance with clinical tasks, as well as guarantee the effectiveness, reliability and safety of its use. This section presents the conceptual principles of building information technology, describes its functionality and provides a context diagram that illustrates the interaction of the system with external entities and information flows.

The input data of the information technology for recognizing pacemaker dysfunction are: subjective health indicators, including a detailed description of the patient's clinical symptoms and complaints; hardware diagnostic reports and system messages generated directly by the internal modules of the pacemaker; results of objective studies of the electrical activity of the heart, in particular classical electrocardiography and long-term daily monitoring using the Holter method; operational data from various sensors specializing in detecting the slightest deviations in the rhythm and nature of cardiac activity in real time.

At the output, the developed information technology forms a comprehensive result, which includes practical recommendations for optimizing parameters and correcting pacemaker settings. In addition, IT provides prompt notification of identified anomalies, addressed directly to the patient, his doctor and trusted persons (relatives) for a quick response to detected dysfunctions.

The functional basis of the developed information technology covers the full cycle of analysis - from the collection of primary complaints to automated decision-making. The main purpose of the system is implemented through the implementation of the following key functions:

- 1) clinical interpretation of the patient's condition – intellectual processing of subjective symptoms, such as dizziness, arrhythmia attacks, general weakness or episodes of loss of consciousness, is carried out, transforming them into structured data for further analysis;
- 2) deep audit of pacemaker parameters – a detailed assessment of the device's internal reports is carried out, which includes monitoring the frequency and mode of stimulation, pulse amplitude, battery level, as well as analysis of intracardiac signals and recorded episodes of arrhythmias;
- 3) dynamic cardiac monitoring – IT provides continuous monitoring of the electrical activity of the heart by analyzing ECG and Holter monitoring results, focusing on the correctness of the interaction of stimulation pulses with the patient's own rhythm;
- 4) detection of anomalies during exercise – the use of specialized algorithms allows you to identify device malfunctions that occur specifically during physical activity, when the cardiovascular system works in a forced mode;
- 5) sensor integration and multiparametric analysis – the technology combines data from various sensors (respiratory rate, intracardiac pressure level, heart rate and body position in space) to create a holistic picture of hemodynamics;
- 6) expert support and communication – based on the processed information, IT generates applied advice on correcting pacemaker settings and instantly sends alarm messages to medical staff, relatives and the patient himself in case of critical deviations.

The context diagram is the highest level of abstraction of functional modeling and reflects the main external relationships of information technology with other entities and systems. This diagram allows you to visually present the general structure of interaction between technology, users and data sources without detailing internal processes. The context diagram of the functional model plays an important role in understanding the boundaries of the system, its functional purpose and the main information flows circulating between it and the external environment.

The context diagram of the information technology for recognizing pacemaker dysfunction is shown below in Figure 1.

In the center of the context diagram is the information technology for recognizing pacemaker dysfunction, which interacts with the following external entities:

- 1) regulatory documentation for the development of information technology;
- 2) the need for the development of information technology;
- 3) researchers, experts in the subject area of information technology, interested parties (patients with cardiovascular diseases, cardiologists);
- 4) notification of the patient, his doctor and relatives about the detected pacemaker dysfunctions;
- 5) recommendations for correcting pacemaker settings;
- 6) methods, principles of information technology development.

The diagram displays the input and output information flows between the system and each of the process participants, which allows you to clearly define the functional boundaries of the technology. The context diagram creates the basis for further detailed functional modeling, in particular, the construction of a precedent diagram and other models.

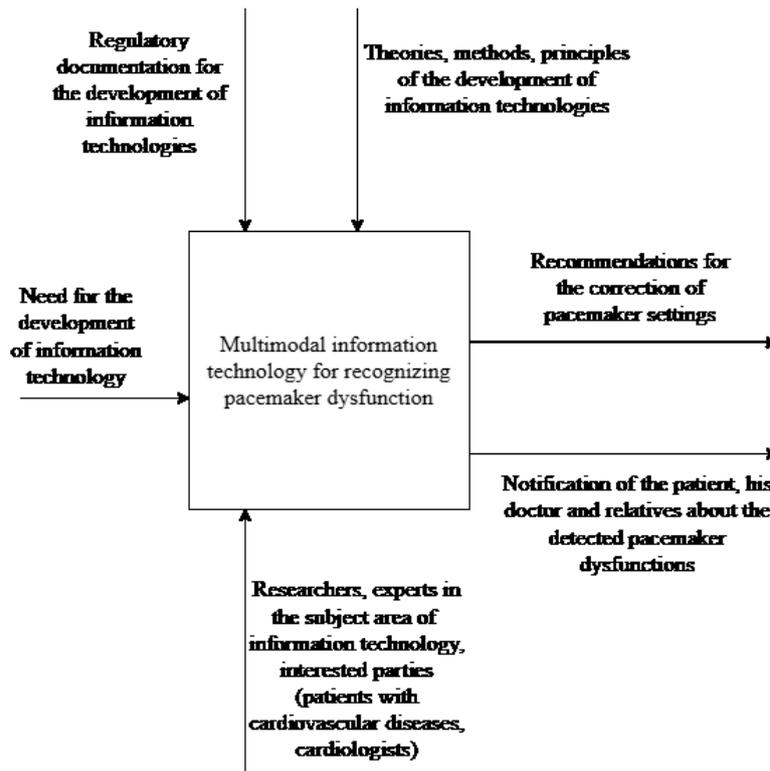


Fig. 1. The context diagram of the information technology for recognizing pacemaker dysfunction

### Modeling the process of recognition of pacemaker dysfunction

Modeling the process of recognizing pacemaker dysfunction is one of the key stages of building information technology that ensures timely diagnostics of deviations in the device's operation. Unlike architectural or mathematical modeling, this type of modeling focuses not so much on the structure or formal dependencies, but on reflecting the functional logic of the system - that is, on how the system performs a sequence of actions for data analysis and decision-making based on certain rules.

To ensure clarity of description and the possibility of further analysis of the process of recognizing pacemaker dysfunction, it is necessary to present such a process in the form of a formalized model based on the apparatus of set theory and mappings of this process. Such an approach will allow generalizing the logic of the functioning of information technology regardless of specific implementation algorithms and software and hardware.

For greater clarity, we present a formal model of the process of recognizing pacemaker dysfunction. Representing the process as a set of sets allows us to describe information technology as a holistic system, clearly distinguish data, states, transformations and results, and provide a formal basis for analyzing the correctness and completeness of the recognition process. Formal model of the process of recognizing pacemaker dysfunction  $M$ :

$$M = (X, S, T, Y, R), \tag{1}$$

- where  $M$  is the process of recognizing pacemaker dysfunction;
- $X$  is the set of input data;
- $S$  is the set of process states;
- $T$  is the set of data transformation operators;
- $Y$  is the set of recognition results;
- $R$  is the set of recommendations and notifications.

The set  $X$  is a formalized description of all the information that the system receives from the outside to perform the recognition process. It combines both objective measured signals and subjective data received from the patient. It is formed as a union of several subsets:

$$X = X_{ecg} \cup X_{dev} \cup X_{sens} \cup X_{symp}, \tag{2}$$

- where  $X$  is the set of input data;
- $X_{ecg}$  are the electrocardiogram signals and Holter monitoring data;
- $X_{dev}$  are the diagnostic data and messages from the pacemaker;
- $X_{sens}$  are the data from physiological sensors;

$X_{symp}$  is the information about the patient's subjective symptoms.

Each of the subsets contains a set of parameters that characterize the state of the patient's cardiovascular system and the pacemaker's operating modes.

The process of recognizing pacemaker dysfunction is described by a finite set of states  $S$ . It describes discrete logical states in which the recognition process can be. Each state corresponds to a completed stage of information processing::

$$S = \{s_0, s_1, s_2, s_3, s_4\}, \quad (3)$$

where  $S$  is a set of process states;

$s_0$  is a state of input data collection;

$s_1$  is a state of primary data processing and normalization;

$s_2$  is a state of analysis and feature extraction;

$s_3$  is a state of logical analysis and recognition of dysfunction;

$s_4$  is a state of formation of conclusions, recommendations and notifications.

The transition between states occurs sequentially. Each state has a corresponding stage of the process of recognition of pacemaker dysfunction.

The set of transformation operators:

$$T = \{t_1, t_2, t_3, t_4\}, \quad (4)$$

where each operator  $t_i$  implements the transition between the corresponding states of the process. The operators  $t_i$  do not depend on the specific implementation of the algorithms and reflect the logic of information processing at the conceptual level:

$$t_1: (s_0, X) \rightarrow s_1, \quad (5)$$

$$t_2: s_1 \rightarrow s_2, \quad (6)$$

$$t_3: s_2 \rightarrow s_3, \quad (7)$$

$$t_4: s_3 \rightarrow s_4, \quad (8)$$

The recognition result belongs to the set  $Y$ , and represents the space of solutions that the system can form based on the results of data analysis. This set allows classifying the states of the pacemaker operation, creates a formal basis for assessing the accuracy and completeness of recognition, and serves as an input set for generating recommendations:

$$Y = \{y_0, y_1, \dots, y_k\}, \quad (9)$$

where  $Y$  is the set of recognition results;

$y_0$  is the normal operation of the pacemaker;

$y_k$  is the detected types of dysfunctions.

Based on the recognition results, a set of recommendations  $R$  is formed. This is a mapping that connects the recognition results with practical actions focused on the system users.  $R$  provides a transition from the analytical level to clinical practice, emphasizes the applied value of information technology, and demonstrates the completeness of the recognition process:

$$R : Y \times C \rightarrow Z, \quad (10)$$

where  $R$  is the set of recommendations;

$C$  is contextual information (patient condition, observation history, etc.);

$Z$  is the set of recommendations for the doctor, patient, and authorized persons.

Thus, the formalized model of the pacemaker dysfunction recognition process allows us to present information technology in the form of an ordered system of sets and operators that reflects the logic of data processing at the conceptual level. The proposed model does not depend on specific implementation algorithms and provides a theoretical basis for further development, optimization, and verification of information technology.

The process of recognizing pacemaker dysfunction within the proposed information technology is expedient to consider as a sequence of formal transformations of input data, which are carried out at different stages of information processing. This approach allows to combine a formal model of the process of recognizing pacemaker dysfunction with a practical description of the stages of system functioning.

In general, the recognition process can be represented as the following chain of transformations:

$$X \xrightarrow{t_1} X' \xrightarrow{t_2} X'' \xrightarrow{t_3} Y \xrightarrow{t_4} R, \quad (11)$$

where  $X$  is a set of raw input data;  
 $X'$  is a set of pre-processed and normalized data;  
 $X''$  is a set of informative features;  
 $Y$  is a set of pacemaker dysfunction recognition results;  
 $R$  is a set of recommendations and notifications.

Transformation  $t_1$  corresponds to the stage of primary data processing and performs the transition from the set of raw input data  $X$  to the set of prepared data  $X'$ . At this stage, noise filtering operations, data correctness and completeness verification, and reduction of heterogeneous signals to a single representation format are performed. Transformation  $t_1$  provides the creation of an information basis for further analysis and reduces the impact of artifacts and measurement errors.

Transformation  $t_2$  implements the selection of informative features and reflects the transition from prepared data  $X'$  to the set of features  $X''$ . At this stage, a compact representation of information is formed that preserves the most significant characteristics of cardiac activity and pacemaker operation. Transformation  $t_2$  allows to reduce the dimensionality of the data and increase the efficiency of further analysis.

Transformation  $t_3$  corresponds to the recognition stage and consists in mapping the set of features  $X''$  into the set of results  $Y$ . At this stage, a logical or algorithmic analysis of the features is carried out in order to detect the presence or absence of pacemaker dysfunction, as well as determine the type of violation. The result of the transformation is a formalized conclusion about the state of the device.

Transformation  $t_4$  provides a transition from the recognition results  $Y$  to a set of recommendations and notifications  $R$ . At this stage, contextual information is taken into account, in particular, the level of criticality of the detected situation, the history of observations and individual characteristics of the patient. Transformation  $t_4$  is aimed at forming practically significant decisions for the doctor, the patient and authorized persons.

The specified sequence of transformations corresponds to the stages of the process of recognizing pacemaker dysfunction and provides a logical connection between the formal model of the process and its practical implementation.

### Conclusions

The development and implementation of a specialized information technology for recognizing pacemaker dysfunctions is a critically important step in reducing mortality from cardiovascular diseases. The proposed technology is based on a comprehensive analysis of multimodal data, including not only technical reports of the device itself on the battery status and stimulation parameters, but also objective electrocardiography indicators, Holter monitoring data and subjective patient complaints. Such an integrated approach allows to significantly increase the accuracy of diagnostics, minimizing the risks of misinterpretation of complex algorithms of modern pacemakers, which can often simulate technical malfunctions.

The scientific novelty and practical significance of the article lies in the use of sequential mathematical transformations of data to highlight the most informative features of cardiac activity and the functioning of the implanted device. The information processing process, which includes the stages of normalization, feature extraction and algorithmic recognition, ensures high efficiency of analysis even in the presence of artifacts and measurement errors. This allows not only to state the fact of the presence of a violation, but also to classify the type of dysfunction, which is critically important for making quick clinical decisions in emergency medicine.

The special value of the technology is its ability to adapt to the individual characteristics of the patient and the context of observation, in particular during physical exertion, when the risk of abnormalities is highest. The final result of the work of information technology is not just a dry technical conclusion, but detailed recommendations for correcting pacemaker settings and an automated notification system for doctors, patients and their relatives. Thus, the created information technology provides a continuous cycle of monitoring and decision-making support, which contributes to a significant improvement in the quality of life of patients and increased reliability of life support systems.

### ADDITIONAL INFORMATION

#### AUTHOR CONTRIBUTIONS

Conceptualization, D.M.; methodology, I.H.; validation, D.M.; formal analysis, I.H.; investigation, I.H.; data curation, D.M.; writing-original draft preparation, I.H.; writing-review and editing, D.M.; visualization, I.H.; supervision, D.M.; project administration, D.M. All authors have read and agreed to the published version of the manuscript.

#### DECLARATION ON THE USE OF GENERATIVE ARTIFICIAL INTELLIGENCE TOOLS

In preparing this work, the author used DeepL Translate and Grammarly for: grammar and spelling checks, paraphrasing, and rephrasing. After using these tools/services, the author reviewed and edited the content and takes full responsibility for the content of this publication.

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## МОДЕЛЮВАННЯ ПРОЦЕСУ РОЗПІЗНАВАННЯ ДИСФУНКЦІЇ КАРДІОСТИМУЛЯТОРА

У статті проведено комплексне дослідження, спрямоване на розв'язання актуальної науково-практичної задачі – моделювання та проектування інформаційної технології розпізнавання дисфункцій кардіостимулятора для підвищення ефективності діагностики та надійності роботи систем підтримки життєдіяльності. Актуальність роботи зумовлена стрімким зростанням кількості серцево-судинних захворювань у світі та в Україні зокрема, що призводить до збільшення кількості операцій з імплантації електрокардіостимуляторів, функціонування яких потребує безперервного та високоточного моніторингу. Авторами проаналізовано світовий досвід використання сучасних інструментів діагностики, включаючи нейронні мережі для аналізу рентгенограм, мобільні застосунки для дистанційного нагляду та алгоритми машинного навчання для аналізу ЕКГ, що дозволило виявити відсутність інтегрованих рішень, які б поєднували різні методи виявлення технічних та клінічних збоїв. В основі запропонованого підходу лежить використання мультимодальних вхідних даних, таких як інформація про симптоми пацієнта (запаморочення, аритмія, слабкість), апаратні звіти пристрою (частота стимуляції, стан батареї, внутрішньосерцеві сигнали), результати ЕКГ і холтерівського моніторингу, а також дані з датчиків фізичної активності та внутрішньосерцевого тиску. Наукова новизна дослідження полягає у розробці математичної моделі процесу розпізнавання дисфункції кардіостимулятора, представленої у вигляді послідовності кортежів та перетворень, що забезпечують підготовку даних, виділення найбільш інформативних ознак серцевої діяльності та безпосереднє розпізнавання стану системи. Особливу увагу приділено етапам нормалізації сигналів та фільтрації артефактів, що гарантує високу точність класифікації порушень навіть за складних умов експлуатації або під час фізичних навантажень пацієнта. Практична значущість роботи підтверджується створенням структури вихідних результатів, які включають не лише автоматизовану фіксацію аномалій, а й формування конкретних рекомендацій щодо зміни налаштувань кардіостимулятора та миттєве сповіщення медичного персоналу, родичів і самого пацієнта. Запропонована технологія дозволяє забезпечити безперервний цикл моніторингу, мінімізувати ризик людської помилки при інтерпретації складних діагностичних даних та суттєво покращити прогноз для пацієнтів із високою залежністю від штучного водія ритму. Таким чином, отримані результати створюють надійний фундамент для побудови сучасних інформаційних технологій кардіологічної допомоги.

Ключові слова: серцево-судинні захворювання, кардіостимулятор, дисфункція кардіостимулятора, інформаційна технологія, моніторинг серцевої діяльності, електрокардіографія, розпізнавання аномалій, математичне моделювання, обробка діагностичних даних, підтримка прийняття рішень, автоматизоване інформування, сенсорна інтеграція.