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BIOMETRICAL ANALYSIS

The contemporary ways of introduction ECG technology: ML, telemetry and bioauthentification

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ABSTRACT

It has been exactly 180 years since the pioneering work of Dr. Carlo Matteucci, professor of physics at the University of Pisa (1842), laid the basis of the method for the registration of biopotentials generated by muscles. In particular, these studies have found practical application in the principal non-invasive method of functional diagnosis of the cardiac muscle – electrocardiography (ECG). Almost a century has passed since this method became recognized and widely used in the clinic. However, to date, it has not only retained its importance in practical medicine but also remains a valuable diagnostic tool. This method allows understanding and effectively prevents errors in the present and future repetition. There are observed favorable trends of ECG-based diagnostics systems implementation and improvement in functional assessment of myocardium electrophysiological characteristics, which reflect cardiovascular pathological vital markers. The essential aim of this article is to demonstrate modern approaches of implementing ECG technology to various fields of medicine and health informatics. This research demonstrated a large number of modern innovations devoted to the automation and modification of implementation of this electrophysiological method and the possible ways to implement it in matters of home and individual monitoring of patients. Furthermore, the review examines the socio-economic issues of deploying and administering tele-ECG technologies to follow up on the global principles of digitization of healthcare and on-site diagnostics by emergency medical services *(Tab. 2, Fig. 4, Ref. 87)*. Text in PDF *www.elis.sk*

KEY WORDS: electrocardiography, tele-ECG, user bioauthentification.

Introduction

Cardiovascular diseases are increasingly becoming an epidemic, arousing heightened interest in the problems of their prevention and diagnosis (Lüderitz and de Luna; 2017; de Luna, 2019). New prospects for improving the diagnosis and prediction of the health status of human-machine systems operators are seen in the collaboration of doctors and engineers, mathematicians and programmers, and representatives of various scientific fields (Rautaharju, 2016; Ljung et al, 2018; Hwang et al, 2019; Reading et al, 2018).

The definition of "functional disorder" does not have clear parameters since these dysfunctions are related to a particular medical specialist's subjective perception and experience. However, there are definite abnormalities caused by human-induced impacts, inflammatory infiltration, and dystrophic processes causing changes in the electrolyte balance and tissue density. They can manifest themselves as a part of diastolic, systolic dysfunction, remodeling of heart vessels, and rhythm and conduction disturbances, which can be the object of monitoring of electrophysiological measurements beyond the reference limits of the norm during acute or chronic periods of myocardial diseases (de Luna, 2019; Klabunde, 2017).

Despite the emergence of the latest methods of functional diagnosis, electrocardiography is still not inferior to its position (Ljung et al, 2018; Shekatkar et al, 2017). Due to the uniqueness of the data obtained and the originality of the technique used, it is still the primary method for instrumental diagnosis of myocardial infarction, arrhythmias, pathology of the cardiac conduction system, and other diseases accompanied by circulatory disorders (Hwang et al, 2019; Haqqani and Marchlinski, 2019; Esina et al, 2021).

From the scientific works of the founders of ECG, it is well known that the potentials occurring during excitation and contraction of the myocardium do not exceed 0.001–0.002 V (Lüderitz and de Luna; 2017; de Luna, 2019). These potentials can be registered only after preliminary amplification (Pfurtscheller et al, 2017; Blackburn et al, 1960; Rudy, 2019; McManus, De Vito and Lowery, 2020). The electrocardiograph is an amplifier com-

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bined with a tape drive mechanism (Fig. 1). In this scheme, the milliammeter needle is replaced by a particular writing device, which leaves a trace on the paper, moving at a certain speed. It is this trace that is the electrocardiogram.

At the same time, it has not been possible to create a theory that would adequately explain the processes occurring during the work of the heart during more than a hundred years of clinical application of electrocardiography (1903) (Pfurtscheller et al., 2017; Melkonian, Blumenthal and Barin, 2018; Blackburn et al, 1960). This circumstance complicates the clinical interpretation of electrocardiograms. It coerces to apply conditional codes, such as the commonly used Minnesota Code, which Dr. Henry Blackburn developed in the late 1950s (Melkonian, Blumenthal and Barin, 2018; Blackburn et al, 1960).

Materials and methods

This study reviewed contemporary publications related to applying and implementation of ECG technology. The following international research databases were used during the study: PubMed, Scopus, Web of Science, Cochrane, etc.

The search and selection of the essential literature was carried out according to the following terms: “ECG”, “ECG telemetry”, “user bioauthentication”, “machine learning”, etc.

As a result of selection, 87 studies were selected for review. 5 of them were reviews and meta-analyses, and the rest of the articles presented the original experience in the implementation and application of authentication methods, as well as the results of using ECG in telemetry and telemedicine.

According to the selected material, the main purpose of the study was analyzing the current possibilities of application and modification of ECG technology for solving goals in the fields of medicine, sport activity and cybernetics.

Results

ECG computerization capabilities

The application of digital equipment and the inherent accuracy of its measurements provides a greater volume of valuable

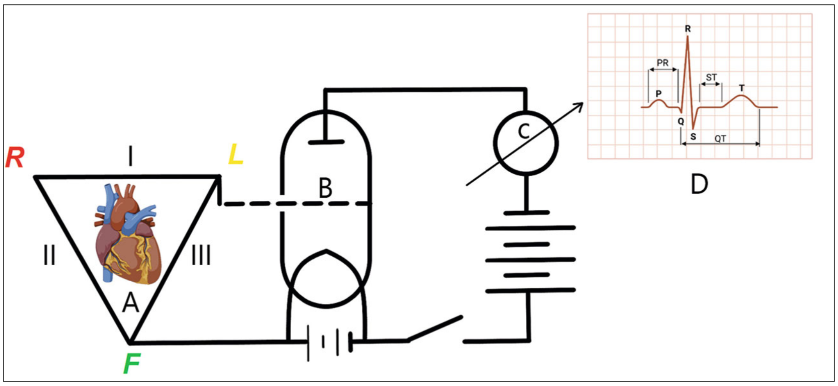

Fig.1. The principal scheme of the ECG method. A – standard leads according to Einthoven; B – triode; C – milliammeter; D – tape drive mechanism with a writing pen and electrocardiogram parts.

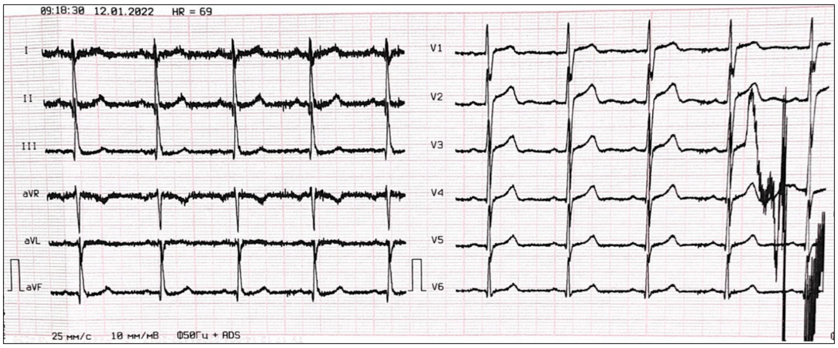

Fig. 2. Interference not related to the influence of EMR (technological) (Image: personal archive of N.A. Konoreva).

Fig. 3. Combined interference (Image: personal archive of N.A. Konoreva).

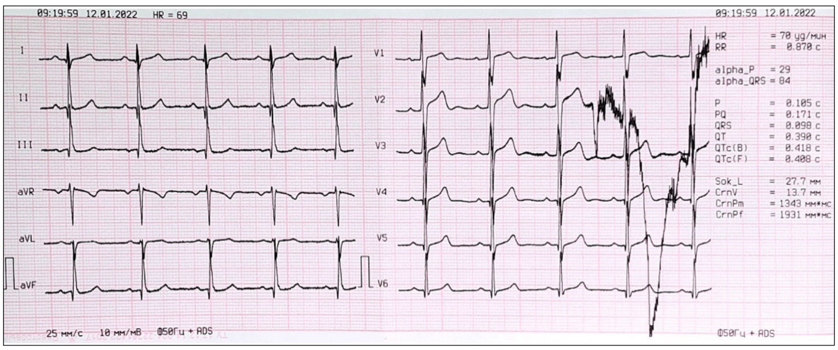

Fig. 4. High-amplitude impulse noise caused by EMR. (Image: personal archive of N.A. Konoreva)

information (Rautaharju, 2016; Loewe, Wülfers, and Seemann, 2018; Hwang et al, 2020; Polak et al, 2018). A lot of worldwide research is devoted to optimizing diagnostic algorithms, systematization, and analyzing ECG signs of myocardial lesions (Hwang et al, 2020; Christov, Raikova and Angelova, 2018; Derganc and Gomiščk, 2021).

Technical requirements for electrocardiographs are defined by international standards IEC 60601-1: 1988, IEC 60601-2-25: 1993, IEC 60601-2-51: 2001. Devices with syndromic diagnostics and "machine" versions of conclusions are increasingly being applied and actively implemented in health care and home individual monitoring of patients (Chiabrando et al, 2020; Bokeria, Makarenko and Kosareva, 2020; Derganc, and Gomiščk, 2021).

Initially, signal averaging (SAECG) or high-resolution ECG (HRECG) for detecting the His bundle signal from the body surface was used to isolate the P-Q segment. The first studies were carried out by E. Berbari et al (1973) on animals and J.B. Uter, C.J. Dennet and A. Tan (1978) on humans in 1978. This method was tested by J. Rozanski in 1981 when assessing the phenomenon of late ventricular potentials (LVP) by means of surgical treatment of ventricular tachycardia (VT) (Rozanski et al, 1981). M. Simson had the most significant influence on developing this type of ECG signal processing, showing the mutual influence between PVC and VT inducibility (Uter, Dennet and Tan, 1978; Rozanski et al, 1981). In 1991, the Expert Committee, which included representatives of the European and American Heart Association of Cardiologists, approved the principles and foundations for the functioning of SAECG and standardized the metrics for interpreting the results of this type of ECG in medical practice (Berbari et al, 1973; Uter, Dennet and Tan, 1978; Rozanski et al, 1981).

This method averages a set of equivalent cardiocycles and makes it possible to consider low-amplitude valuable signals. The application of electrodes occurs according to an orthogonal scheme applying bipolar leads. The most common signal processing method is the averaging of successive cardiocycles. Further, its frequency decomposition occurs (fast Fourier transform or Wavelet processing) and post-filtering (Berbari et al, 1973; Uter, Dennet and Tan, 1978).

Future trends in ECG-related research, for the most part, are classified into three categories: improving ECG recording devices, intelligent analysis of ECG data (telemedicine, digital medicine and home health care, applications for smartphones), and improving the accuracy of ECG diagnosis and application (self-diagnosis, real-time monitoring, the implementation of portable wireless ECG monitoring systems) (Rautaharju, 2016; Wiśniowska, and Polak, 2018; Bokeria, Makarenko, and Kosareva, 2020; Loewe, Wülfers and Seemann, 2018) (Tab. 1).

The application of digital equipment and the inherent accuracy of its measurements provides a greater volume of valuable information (Rautaharju, 2016; Loewe, Wülfers, and Seemann, 2018; Hwang et al, 2020; Polak et al, 2018). A lot of worldwide research is devoted to optimizing diagnostic algorithms, systematization, and analyzing ECG signs of myocardial lesions (Hwang et al, 2020; Christov, Raikova, and Angelova, 2018; Derganc, and Gomiščk, 2021).

ECG as biometric user authentication

Remote forms of information transfer are increasingly replacing traditional methods of sending and receiving data. However, the globalization of the world's communications systems is, in some cases, actively opposed, including in the form of terrorism (Lu et al, 2015; Pelc, Khoma and Khoma, 2019; Brás, 2018; Barros, 2020; Chou et al, 2020; Krasteva, Jekova and Abächerli, 2017; Antonioletti et al, 2017; Richter et al, 2017). This is another argument in favor of further improving methods of identification.

The primary priority is confirmation. This definition is connected with identifying the person and parties to the communication. For more than a century, electrocardiography (ECG) has been applied in clinical practice. Accumulated experience demonstrates that ECG contains not only signs of a particular disease. In addition, it is strictly related to individual characteristics that could be used for biometric identification (Lu et al, 2015; Pelc, Khoma and Khoma, 2019; AlDuwaile and Islam, 2021; Jekova, Krasteva and Schmid, 2018).

The identification process involves comparing a reference sample with an identifiable object (Louis, 2017; Jekova, Krasteva and Schmid, 2018; Richter et al, 2017). The chosen identification method should combine the versatility of the studied parameters with their unique features, constancy, and reproducibility. Furthermore, these parameters should not lend themselves to imitation and, depending on external circumstances, be available for comparison with the benchmark (Bogun, and Saeed, 2017; Antonioletti et al, 2017; Missel, et al. 2020; Zhou, et al. 2020). Given these requirements, ECG appears to be an up-and-coming method of biometric identification.

Surface potentials induced by the heart's electrical activity are tens to hundreds of magnitude inferior to natural and artificial external fields. In addition, the patient is not only a generator of biopotentials but also an antenna for external EMR (Fig. 2). This phenomenon occurs in a conductor placed in an electromagnetic field.

The following could be used as standard identification markers: duration of electrical systole (Bazett's formula); proposed by L.I. Fogelson and A.I. Chernogorov systolic index and indicator; the electrical axis of the heart, determined by Dyed's table.

Additional markers: the ratio of the R-S amplitude to the Q-T interval; the ratio of the Q-T interval to the T-Q interval; the ratio of the P-Q interval to the R-S amplitude, the P-Q interval to the Q-T and R-R intervals.

All measurements and calculations are performed in the second standard lead ("II standard" according to Einthoven), or in Neb: "A" only, or (if necessary) in any of the leads (D, A, I) (Chou et al, 2020; AlDuwaile, and Islam, 2021; Hong et al, 2019).

Applying markers increases the level of "individualization" of ECG by eliminating or significantly reducing the probability of complete or partial coincidence. Each indicator must comply with biometric identification requirements in randomly selected ECG (AlDuwaile, and Islam, 2021; Hong et al, 2019; Krasteva, Jekova, and Abächerli, 2017).

Along with the undoubted prospects and advantages of electrocardiographic identification, it is necessary to consider several problems. Those barriers included vulnerability to electromagnetic interference, circadian rhythms, physical and emotional stress,

Tab. 1. Examples of contemporary multifunctional systems of ECG diagnostic platforms for detection of cardiac disorders and pathologies.

Pathologies, disorders1	The essential ECG markers and technical ways to improve their diagnostic potential	Ref
Cardiac ischemia	A deviation of the ST segment by more than 0.5 mm from the isoline and the appearance of a „coronary“ T-wave (high (usually more than 1.0 mV in the chest leads), pointed, symmetrical T wave. The application of K-point as an author's model for detecting ischemia markers increased the specificity by 7–10% compared with standard 12-lead ECG	(Loewe, Wülfers and Seemann, 2018)
Arrhythmia induced by drugs	Prolonged QT interval is a marker of high-risk of occurrence of Torsade de Pointes (TdP). Reflecting this statement researches suggested their own model based on electrophysiology of single cells for early diagnostic of drug induced arrythmia . The most essential results connected with mathematical model of classification TdP patterns. The best model got accuracy metrics for a validation dataset: ROC = 0.82 and accuracy = 0.83	(Hwang et al, 2020; Polak et al, 2018)
Brugada syndrome (BS)	A deviation of the ST segment by more than 0.5 mm or an extended duration of J-wave and polymorphic ventricular tachycardia (PVT) in the V1–V3 leads. The research of 5500 ECG recordings was performed, less than 1% of which were associated with BS. The essential results are associated with detecting specific patterns of baseline ventricular stimulation cycle durations of 600, 500, and 400 ms due to algorithms of timeseriesd analysis	(Calloe, et al, 2018; Schwarzwald. 2019)
Idiopathic ventricular arrhythmias (IVA)	The QRS duration is 160 milliseconds, an independent P wave is seen in lead II and an offset of the electrical axis to the left. The research examined ECG data from 63 patients with IVA. An algorithm related to the 4 anatomical quadrants, the precordial transition, the duration of the ventricular complex, and the presence of specific morphology in certain leads was implemented. The accuracy of the algorithm was evaluated on the ablation success of 12 patients and was 92%	(Enriquez et al, 2019; Uter, Dennet and Tan, 1978)
The Wenckebach Phenomenon	The PR interval gradually lengthens until a QRS follows one P-tooth. Mathematically, the gradual lengthening of the PR interval was calculated. The model defines that the pause caused by an unconducted P wave is equal to the increment between the last PR interval and the first PR interval following the pause subtracted from doubled the PP interval	(Hansom, Golian, and Green, 2021)
Ebstein's anomaly (EA)	High peak-shaped P waves and right bundle branch block with no signs of right ventricular hypertrophy. Right ventricular tension was reduced, as evidenced by a decrease in RMSV2 (0.6 ± 0.4 mV) and vectors of 10-20 ms. Decreased RMSV is directly related to the presence of TI3 in patients	(Liu et al, 2021)
False heart abnormalities	ECG signal amplification in the range of 1–5 mV. The interval of ECG amplifier values in the lead is ±5 mV with an error of less than ±20%. The research accomplished 1.25 million ECG recordings from different ECG databases. The accuracy metrics of classification of false alarm detection was 90%.	(Krasteva, et al, 2016)
Atrial fibrillation	Atrial fibrillation is characterized by irregular QRS complexes and f waves in leads V1, II, III and AVF The result was the assessment of f1-score metrics for the atrial fibrillation (0.81). A total of 44 features were used, the main ones being heart HRV4, average beat morphology, atrial f-waves	(Christov et al, 2018; Krasteva et al, 2021)
Tachycardia	To detect tachycardia, frontal and horizontal percent amplitude change and percent time-voltage area change were assessed, broadly assessing changes in QRS complex amplitude-range (µV) and time-voltage area (µV·ms). The most appropriate models of Evenson et al of logistic regression are the wide QRS complex tachycardia (WCT) Formula (AUC 0.97), Ventricular tachycardia (VT) Prediction Model (AUC 0.9), and WCT Formula II (AUC 0.96). The model of Poptano et al has been established with approximately 91% accuracy in distinguishing these types of narrow tachycardia	(Evenson et al, 2021; Poptani et al, 2021)
Bradycardia induced by drugs	Frequent ventricular extrasystoles, prolongation of QRS complex, decreased ST segment, depressed or inverted T wave, pronounced U wave. Authors calculated mean QTc values and QTc substitutes induced by decreased plasma potassium levels were below thresholds of particular concern: QTc duration < 500 ms and change of 30 or 60 ms. It gained new statistically significant features and improved quality of diagnostics	Wiśniowska, and Polak, 2018;
Supraventricular arrhythmia and tachycardia	QRS complexes are usually narrow, following frequently and rhythmically; however, there may also be wide QRS, which must be differentiated from ventricular tachycardia. A study of Ali et al demonstrated applying of timeseries algorithms for clinical case, and the main ECG features with a relatively low heart rate of 90-100 bpm were dissected. This change was due to narrow QRS complexes without a well-defined P wave. Aresearch of Tabing and al demonstrated the clinical case of patient whose heart attack was diagnosed with AliveCor Mobile ECG (smartphone-based device and ECG application)	(Ali et al., 2019; Tabing et al, 2017)
Myocardial infarction (MI)	The absence of the R wave characterizes inferior MI, abnormal Q wave (where the Q/R amplitude ratio > 0.25), upward deviation of the ST segment above the isoline, and negative T wave, in leads II, III, and AVF. The study demonstrated 2362 patients, 42% of whom were assigned to the group with ST segment elevation MI, 16% with ST-elevation inferior MI, and 42% of patients with chest pain were selected randomly. The new statistically significant signs of lower localized MI included ST-segment elevation in the III lead, ST-segment deviation in the V4-V6 leads without V2, and ST-segment amplitude in V1 higher than V2	(Hock et al, 2021)
Shockable and Non-Shockable Rhythms	Alternating attacks of atrial fibrillation and sinus bradycardia with HR < 40 bpm, long or short pauses of more than 2 seconds in the sinus node, recurrent CA block with pauses of more than 2 seconds. The final author's dataset consisted of 10,000 parameters of ECG, Holter monitoring, and defibrillator recordings for the most accurate estimation of ECG signal propagation time series (AUC = 0.97)	(Krasteva et al, 2020)

Tab. 1.

Pathologies, disorders1	The essential ECG markers and technical ways to improve their diagnostic potential	Ref
Assessment of cardiac resynchronization therapy. Patients with New York Heart Association (NYHA)	Patients with NYHA class II, III, or IV heart failure present with prolonged QRS interval (≥ 130 milliseconds), especially in the form of a typical left bundle branch block. Authors built their own model for improvement of assessment of cardiac resynchronization therapy. Training dataset consisted of 34 patients receiving cardiac resynchronization therapy (CRT). Electrical (RV-LV delay) and mechanical (time to peak contraction) indices correlated with an improved acute hemodynamic response (AHR) with an accuracy of 70 ± 11% and an AUROC curve of 0.73	(Lee et al, 2021)
Cardiac Arrest Rhythms during Cardiopulmonary Resuscitation	Ventricular fibrillation or asystole with the sum of positive and negative maximum peak moduli relative to the isoline of more than 200 μV. Building of neural networks models and filtering algorithms for cleaning electrocardiogram data from artifacts and estimation of physiological parameters of patients with AUC = 0.9	(Brandt and Gulba, 2006)
Origins of Idiopathic Ventricular Arrhythmia	The premature appearance of a QRS complex dilated and deformed relative to the main rhythm without a preceding P wave, excluding late extrasystoles preceded by P waves. Automatic Arrhythmia Origin Localization system created by researchers indicated the localization of the origin of idiopathic ventricular arrhythmia on the patient-specific geometry of the left ventricle, right ventricle, and adjacent vessels due to incomplete EAM. The best model achieved a localization accuracy of 3.6 mm	(Hwang et al, 2020)
Signals recorded with incorrect overlapping leads	Lead I become inverted; the vector of the QRS complex in the lead I does not coincide with lead V6; leads II and III change places; leads AVL and AVR change spots; in most cases, the PQRST complex in lead aVR becomes positive; lead aVF remains unchanged. The author's resulting model is connected with high precision metric AUC = 0.93 for distinguishing incorrect overlapping leads and informs the user about incorrect electrode placement	(Buttà et al, 2020)
High arrhythmic risk in antero-septal acute myocardial ischemia	Horizontal or oblique ST-segment deviation from isoline and negative T wave. Researchers shared their experience of modeling various scenarios of ischemia applying mathematics and geometry methods based on electrophysiology of the heart. The possibility of three-dimensional modeling and display of anterior septal acute myocardial ischemia was shown that increased the quality of diagnostic the ischemia.	(Martinez-Navarro et al, 2019)

[1] Pathologies, symptoms, or syndrome of disorders or anomalies of electrophysiological parameters of the heart; [2] RMSV – right maximal spatial voltage; [3] TI – tricuspid insufficiency; [4] HRV – rate variability analysis

heart rate variability, and other factors due to long-term exposure to lifestyle and work patterns (Antonioletti et al, 2017; Missel et al, 2020; Zhou et al, 2020; Németh et al, 2016).

High sensitivity allows increased electricity capacity thousands of times. It makes the technical diagnostic tools extremely vulnerable to various interferences. Undesirable physical phenomena and effects of EMR interfere with the work of diagnostic equipment, reshaping their characteristics and parameters. All of them are referred to as electromagnetic interference (Bokeria, Makarenko, and Kosareva, 2020; Loewe, Wülfers, and Seemann, 2018; Krasteva et al, 2020; Louis et al, 2017).

When analyzing the ECG, it should be remembered that tissue electrical resistance (baseline impedance) varies depending on the blood supply (Fig. 3). These changes are barely a hundredth of a base impedance. In this sense, an electrocardiogram is also a rheogram, registering transformations in electrical resistance depending on the degree of blood filling of tissues (Calloe et al, 2018; Christov, Raikova, and Angelova, 2018).

A review of the available information allows us to consider the application of the ECG as a biometric identification signal encouraging (Lu et al, 2015; Chou et al, 2020; AlDuwaile and Islam, 2021). Regular electrocardiographs with a frequency of 500 Hz are suitable for this purpose. Low-frequency noise in the spectrum is located at less than 1 Hz, which manifests as a "wandering" isoline. It is caused by respiratory excursions of the chest, unsatisfactory contacts on the electrodes, etc.

High-frequency noise can be detected "inside" an individual heartbeat (Fig. 4). Noise suppression is possible with digital Butterward filters or wavelets. As a result, of one-dimensional signal processing, medical specialists get a matrix of helpful information. Furthermore, a typical heartbeat pattern is obtained from this matrix. Time and amplitude distances are calculated from the pattern's reference points. Some researchers distinguish analytical signs - signal decomposition coefficients on a variety basis (Fourier, cosine, wavelets, etc.) (Christov, Raikova, and Angelova, 2018; Krasteva et al, 2020, 2021; Brandt, and Gulba, 2006; AlDuwaile and Islam, 2021).

A comprehensive fundamental model of the identification system could be built by incorporating archival data of electrocardiographic and other functional studies with topical diagnostics of coronary circulation disorders and some other typical differential diagnostic signs of ECG, particularly blockages and arrhythmias.

Tele-ECG in remote diagnostics and sports

Remote forms of diagnostics are becoming increasingly common, not only in medicine but also in sports (Winkelmann, and Crossway, 2017; Sharma et al, 2017; Léger et al, 2016; Dhutia et al, 2016; Albiński et al, 2021; Prutkin, and Drezner, 2017; Gillinov et al, 2017). This is to improve the quality of performing "natural" physical tests or achieving the most optimal indicators in training athletes and achieving maximum training efficiency (Dhutia et al, 2016; Corrado et al, 2020; Corrado and Zorzi, 2017; Cunningham, Maghrabi, and Sanatani, 2017). The development of this trend is evidenced by the fact that many sports centers are beginning to have functional diagnosticians who evaluate the myocardium's state at different training moments (Sharma et al, 2017; Brosnan, and Rakhit, 2018; Gillinov et al, 2017; Corrado and Zorzi, 2017; Cunningham, Maghrabi, and Sanatani, 2017).

Tab. 2. Possibilities and limitations of Tele-ECG diagnostic systems.

Possibilities	Models of implementation	Refs	Limitations	Possible models of implementation	Refs
A method for overcoming the lack of access to healthcare facilities. Smartphone-based telemedical ECG aid for primary care physicians. It is an optimal cost-efficient strategy with easy replication all over the globe.	Applying automated machines and information transfer devices; trained medical personnel; implementation of scientific and state programs	(Mappangara et al, 2020; Maciel, Irigoyen and Goldmeier, 2019; Chauhan et al, 2018; Lazarus, Kirchner and Siswanto, 2020; Alkmim et al, 2019; Bediang et al, 2022)	Mass communication through specialized, cost-effective, needs-based information modules. Education and training of medical personnel.	Perfoming of the investment appeal of regions; subsidizing infrastructure development in remote areas from economic centers	(Ganapathy et al, 2019; Bediang et al, 2022; Cui et al, 2020)
Immediate primary medical triage of patients increases the probability of early hospitalization of patients by indication.	Extensive use of information and communication technologies and data transfer methods	(Mappangara et al, 2020; Lazarus, Kirchner and Siswanto, 2020; Gröschel et al, 2020)	Presence of multilingual regions and districts Presence of traditions and characteristics of multi-ethnic groups	Improving the general level of literacy of the population; explaining the need for medical manipulations	(Mappangara et al, 2020; Ganapathy et al, 2019; Bediang et al, 2022)
Implementing a tele-ECG system in conditions of nonavailability of emergency healthcare services in mountainous, isolated, and sparsely populated regions. The region has a poorly developed economy and infrastructure	State subsidization of the development of the technologies in question; attraction of investment and development of tourism with developed medicine	(Ganapathy et al, 2019; Bediang et al, 2022)	Risk of interrupted power supply.	Formation of additional units and modules for autonomous energy, electrical substations	(Ganapathy et al, 2019; Ohligs et al, 2020; Cui et al, 2020)
Building an extensive telehealth network can be helpful for further developments in the field of digital electrocardiography, clinical cardiology, and cardiovascular epidemiology. Implementing machine-learning algorithms to improve the diagnostic capabilities of physicians.	Increased cooperation between medical and scientific-educational institutions; application of modern methods of data organization and processing	(Ribeiro et al, 2019; Gröschel et al, 2020)	It increased non-medical general hospital staff for developing and supporting the digital medical ecosystem. Additional financial maintenance for system administrators and technical support groups in case of equipment interruptions.	Providing additional opportunities and benefits for staff to work in hard-to-reach areas; increasing government spending in the social sphere	(Ganapathy et al, 2019; Bediang et al, 2022; Cui et al, 2020)
The tele-ECG allows an early diagnosis of ACS, reducing the delay to definitive treatment, whether reperfusion, chemical, or mechanical therapy.	Implementation of applications with biomedical data transfer capability and their interpretation by primary care physicians	(Maciel, Irigoyen and Goldmeier, 2019; Chauhan et al, 2018)	The establishment of specialized medical equipment and software with the ability to receive and transmit data with confidentiality. Maintaining a stable Internet network for stable data transmission.	Applying closed communication channels, the transmission of main data arrays through the primary and backup cables	(Ohligs et al, 2020; Lilienthal, and Dargie, 2021)
Reducing the number of home visits by doctors. Reducing the number of false calls to doctors due to angina attacks in the elderly.	Developed medical information infrastructure; ability to transmit different types of information	(Ohligs et al, 2020)	Potential difficulties in properly conducting an ECG examination by specialized medical personnel or trained family members.	Teaching the principles of first aid and explaining the methodology of routine ECG	(Ohligs et al, 2020; Lilienthal, and Dargie, 2021)
Reducing the number of contacts with infectious patients during a pandemic (COVID-19).	Applying modern sensors with the possibility of primary data processing and transmission via Wi-Fi	(Gröschel et al, 2020; Bediang et al, 2022)	Enhancing security for data retention and transfer.	The application of modern data encryption technologies and their transmission over closed communication channels	(Cui et al, 2020)
The potential for the application of new devices to overcome the limitations of the methods used for assessing the functional state of the myocardium.	Implementing specialized filters and machine learning techniques to level out changes	(Lilienthal, and Dargie, 2021)	Difficulties are interpreting noises during the ECG examination and/or losing some information during transmission.	Development of new methods for the transfer and preservation of information	(Maciel, Irigoyen and Goldmeier, 2019; Gröschel et al, 2020; Cui et al, 2020]

Exercise tests are one of the essential functional tests in the ECG. One of the most common is the treadmill test. Its implementation consists of installing a wearable electrocardiograph and running the patient along the treadmill with a certain inclination to form an ECG during exercise. This test allows for a complete diagnosis of cardiac diseases that do not manifest themselves in a state of rest. Also, the degree of tolerance (endurance) of the body to physical activity is determined, and heart rhythm disturbances are detected. This study is currently widely used in gyms to prevent ischemic changes in the heart and improve the quality of physical training (Sharma et al, 2017; Léger Sharma et al, 2016; Dhutia Sharma et al, 2016; Gillinov et al, 2017; Corrado and Zorzi, 2017; Cunningham, Maghrabi, and Sanatani, 2017).

Continuous remote monitoring of electrophysiological parameters of the heart of patients who are vulnerable to cardiogenic morbid conditions, and at the same time living in remote areas, insufficiently equipped medical institutions, will reduce the risks of fatal conditions and the economic burden on the health care (Calloe et al, 2018; Poptani et al, 2021; Uter, Dennet, and Tan, 1978). For the implementation of this approach, it is necessary to have the following components: the presence of data centers in regional cities, where ECG data will be stacked; laying of networks for the high-speed Internet connection; deployment of information infrastructure on the client and server sides (Evenson et al, 2021; Wiśniowska and Polak, 2018; Rozanski et al, 1981) (Tab. 2).

Discussion

In our contemporary life, the essential issues of the implementation and use of the ECG were raised by the necessity to take into account the various characteristics of living beings. Even though no more than 100 years have passed since the creation of the most important method for diagnosing heart pathologies, this method is still relevant.

This is confirmed by the fact that researchers are working on improving the quality of diagnostics and recognition of ECG records with the expansion of possible ways to prevent cardio morbid conditions of patients of cardiology and cardiac surgery departments in hospitals.

Also, this method is considered from the standpoint of implementation not only in the medical field of activity, but also in sports and cybersecurity. The first area has found application as a tool to improve the quality of training for athletes and control the state of the myocardium during physical exertion. From the point of view of biometrics, this method has also proven itself, taking into account the possibility of registering personal electrophysiological characteristics of the heart of each person, which can be used as a means of user authentication in cybernetic systems.

Conclusion

Regarding biometric identification, scientists propose using the ECG to identify indicators. These features persist for a relatively long (for practical purposes) time, and allow calculations of special indices on this basis. The proposed solution eliminates the simple "comparison" of the reference ECG copy with the proposed variants. Using a program similar to the Minnesota code, medical practitioners and scientists can get information not only about the degree of ECG deviation from average values but also solve the problems of biometric identification. At the same time, it is enough to register only one lead from two standard points.

Thanks to the development of distance technologies, their application, and implementation in health care practices, there are prerequisites for reaching a more significant number of people living in areas remote from regional economic and core-infrastructure centers. In many countries, tele-ECG is already considered the standard of primary diagnosis in emergency medical services. There is also a demand for monitoring heart indicators among athletes to improve the quality of exercise and training in general.

Holter monitoring, being an addition to the standard ECG study, allows physicians and scientists to monitor changes in the myocardium when the patient performs routine manipulations day and night. In the primary case, it seems to be as the patterns of progression of symptoms, that in most cases are latent for the patient himself, under the influence of physical or psycho-emotional factors, such as syncope. In the second case, it is possible to determine the functional state of the parasympathetic and sympathetic parts of the nervous system. In addition, daily ECG monitoring allows cardiologists to understand calibration and evaluation of the optimal use of pacemakers in terms of seizure efficiency.

Electrocardiography is one of the necessary methods of functional diagnostics, reflecting the physiological processes of the myocardium. This is because it is non-invasive and with the correct technique implementation. Moreover, it is objective from a clinical and diagnostic point of view to detect ischemic and necrotic changes in tissues, which prevents the occurrence of cardiogenic morbid pathological conditions in patients. The indicators obtained during additional functional tests significantly determine the primary clinical diagnosis and specific therapy.

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