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PHYSICAL AND BIOPHYSICAL FOUNDATIONS OF ECG AND EEG IN MEDICAL DIAGNOSTICS

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Electrocardiography (ECG) and electroencephalography (EEG) are among the most important methods of functional diagnostics. Both methods are based on recording the bioelectrical activity of the heart and the brain. The aim of this study is to review the physical and biophysical foundations of ECG and EEG and evaluate their role in medical diagnostics. The article presents an overview of modern literature describing mechanisms of signal generation, principles of recording, and data interpretation. The analysis confirms that ECG is essential for detecting cardiac arrhythmias, ischemic and conduction disorders, while EEG is widely applied for diagnosing epilepsy, encephalopathies, and sleep disorders. The conclusions emphasize the importance of understanding the physical foundations to improve diagnostic efficiency and to integrate digital technologies.

Keywords: ECG, EEG, biophysics, diagnostics, bioelectrical processes.

Introduction.

Functional diagnostics occupies a special place in modern clinical medicine, allowing for the objective assessment of the condition of organs and systems based on their physiological activity. Among the most widespread and important methods are electrocardiography (ECG) and electroencephalography (EEG), which have long been considered the 'gold standard' in cardiology and neurology [1][2]. The relevance of these methods is determined by the high prevalence of cardiovascular and neurological diseases. According to the World Health Organization, cardiovascular diseases remain the leading cause of mortality worldwide, accounting for nearly 18 million deaths per year [3]. At the same time, neurological conditions such as epilepsy, dementia, and stroke affect more than one billion people globally, representing a massive social and economic burden [4]. In this context, ECG and EEG play a key role in early detection of pathological changes, monitoring disease progression, and providing the foundation for timely and effective treatment.

Aim of the Study

To review the physical and biophysical foundations of electrocardiography and electroencephalography and evaluate their significance in medical diagnostics.

Objectives of the Study

1. To study the biophysical mechanisms underlying the generation of bioelectrical activity in the heart and brain.
2. To review the physical principles of signal registration in ECG and EEG.
3. To analyze the diagnostic value of ECG in cardiology and EEG in neurology.
4. To compare the biophysical principles of both methods.
5. To outline the prospects for the development of diagnostics using ECG and EEG in the era of digital medicine.

Methods

This study was conducted as a literature review. Data sources included international databases such as PubMed, Scopus, Web of Science, and Google Scholar, as well as regional sources, including eLIBRARY and journals of Kazakhstan and CIS countries [1]–[4]. Inclusion criteria: publications describing the physical and biophysical mechanisms of bioelectrical activity, methods of ECG and EEG registration, and their clinical applications. Exclusion criteria: low-quality reviews without references to original studies, and works unrelated to cardiovascular or neurological diagnostics. The search strategy included keywords such as 'ECG biophysics', 'EEG signal analysis', and 'bioelectrical activity diagnostics'. A total of 65 articles were initially retrieved, of which 32 met the inclusion criteria after abstract screening and full-text evaluation.

Results and Discussion

All living cells possess a transmembrane potential, formed by unequal ion distribution and activity of ion channels and pumps. When threshold depolarization is reached, an action potential occurs, serving as the universal signal in excitable tissues [5][6]. In cardiac tissue, specialized pacemaker cells in the sinoatrial node initiate rhythmic impulses that propagate through the conduction system. This results in the coordinated contraction of the atria and ventricles. The ECG reflects the summated electrical activity of the heart: the P wave corresponds to atrial depolarization, the QRS complex to ventricular depolarization, and the T wave to ventricular repolarization [7]. It is based on recording potential differences between body surface points, classically represented by Einthoven's triangle [3].

Similarly, EEG registers summed post-synaptic potentials of cortical neurons. It reflects different brain rhythms: alpha (8–13 Hz), beta (14–30 Hz), theta (4–7 Hz), and delta (0.5–3 Hz). These rhythms are associated with functional brain states such as wakefulness, relaxation, and sleep [8]. EEG is widely used for diagnosing epilepsy, brain injuries, encephalopathies, and sleep disorders. In clinical neurology, EEG serves as a cornerstone for differential diagnosis, monitoring disease progression, and assessing the effects of treatment.

From a biophysical perspective, both ECG and EEG represent examples of volume conduction, where bioelectrical signals generated by excitable cells propagate through tissues and can be detected non-invasively at the body surface. The

amplitude and frequency characteristics of these signals depend on tissue conductivity, electrode placement, and the underlying physiological processes. Noise reduction, signal amplification, and digital filtering remain essential steps in ensuring accurate registration and interpretation of data [6][7].

In recent years, the integration of digital technologies and artificial intelligence has significantly advanced the diagnostic potential of ECG and EEG. For example, machine learning algorithms can automatically detect arrhythmias on ECGs or classify seizure patterns on EEGs with high accuracy. Wearable devices, such as smartwatches and portable EEG headsets, provide continuous monitoring outside hospital settings, increasing accessibility and enabling preventive healthcare [2][4]. However, challenges remain in standardizing data formats, ensuring interoperability, and maintaining patient privacy.

Conclusion

Electrocardiography and electroencephalography are fundamental diagnostic methods based on recording the bioelectrical activity of the heart and brain. While ECG is essential for diagnosing cardiac arrhythmias, ischemia, and conduction abnormalities, EEG plays a critical role in detecting epilepsy, encephalopathies, and sleep disorders. Understanding their physical and biophysical foundations is crucial for improving diagnostic accuracy and fostering the integration of digital technologies in clinical practice. The future of functional diagnostics lies in the interdisciplinary combination of physics, medicine, and data science. Advances in artificial intelligence, big data analytics, and wearable biosensors are expected to expand the role of ECG and EEG in personalized and preventive medicine. For medical students and young researchers, mastering these biophysical principles provides not only theoretical knowledge but also practical skills vital for modern clinical practice.

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ФИЗИЧЕСКИЕ И БИОФИЗИЧЕСКИЕ ОСНОВЫ ЭКГ И ЭЭГ В МЕДИЦИНСКОЙ ДИАГНОСТИКЕ

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Электрокардиография (ЭКГ) и электроэнцефалография (ЭЭГ) являются одними из важнейших методов функциональной диагностики. Оба метода основаны на регистрации биоэлектрической активности сердца и головного мозга. Цель данного исследования — рассмотреть физические и биофизические основы ЭКГ и ЭЭГ и оценить их роль в медицинской диагностике. В статье представлен обзор современной литературы, описывающей механизмы генерации сигналов, принципы регистрации и интерпретации данных. Анализ подтверждает, что ЭКГ играет ключевую роль в выявлении аритмий, ишемических и проводящих нарушений сердца, в то время как ЭЭГ широко используется для диагностики эпилепсии, энцефалопатий и нарушений сна. В заключении подчеркивается важность понимания физических основ для повышения эффективности диагностики и интеграции цифровых технологий.

Ключевые слова: ЭКГ, ЭЭГ, биофизика, диагностика, биоэлектрические процессы.

МЕДИЦИНАЛЫҚ ДИАГНОСТИКАДАҒЫ ЭКГ МЕН ЭЭГ-НІҢ ФИЗИКАЛЫҚ ЖӘНЕ БИОФИЗИКАЛЫҚ НЕГІЗДЕРІ

Балжан Бейбітқызы

Электрокардиография (ЭКГ) мен электроэнцефалография (ЭЭГ) — функционалдық диагностиканың ең маңызды әдістерінің бірі. Екі әдіс те жүрек пен мидың биоэлектрлік белсенділігін тіркеуге негізделген. Бұл зерттеудің мақсаты — ЭКГ мен ЭЭГ әдістерінің физикалық және биофизикалық негіздерін қарастыру және олардың медициналық диагностикалық рөлін бағалау. Мақалада сигналдардың түзілу механизмдері, тіркеу қағидалары және алынған деректерді талдау тәсілдері туралы заманауи әдебиеттерге шолу берілген. Талдау нәтижелері ЭКГ-нің жүрек ырғағының бұзылыстарын, ишемиялық және өткізгіштік ақауларды анықтауда маңызды екенін, ал ЭЭГ-нің эпилепсия, энцефалопатия және ұйқы бұзылыстарын диагностикалауда кеңінен қолданылатынын көрсетеді. Қорытындыда диагностика тиімділігін арттыру және цифрлық технологияларды интеграциялау үшін физикалық негіздерді түсінудің маңыздылығы атап өтіледі.

Кілт сөздері: ЭКГ, ЭЭГ, биофизика, диагностика, биоэлектрлік процестер.