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The 1-minute sit-to-stand test: a simple tool for remote functional assessment in the era of telemedicine

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Abstract. Current challenges facing the healthcare system, particularly the COVID-19 pandemic and military conflicts, necessitate the expansion of remote healthcare delivery capabilities. Telemedicine creates new opportunities for monitoring patients' conditions; however, it requires the implementation of simple, valid, and accessible tools for assessing functional status. Therefore, the aim of this study was to justify the feasibility of using the 1-minute sit-to-stand test for remote assessment of functional ability, as well as to analyze its clinical utility and potential for use in outpatient telerehabilitation. The study was conducted as an analytical review of scientific sources, systematizing data selected from the PubMed and Web of Science databases over the past 10 years. Results indicate that assessing cardiorespiratory interaction during physical exertion and in the recovery period is more informative than analyzing resting parameters; at the same time, cardiopulmonary exercise testing remains the gold standard, but its application is limited by complexity, the need for specialized equipment and high resource costs. The 6-minute walk test partially overcomes these limitations, but is not always suitable for remote use. Against this backdrop, the 1MSTST stands out for its practical utility: it allows for the quantitative determination of exercise tolerance, the assessment of cardiorespiratory response during test and in recovery phase, and identification of signs of reduced physical performance in patients. Its ease of use and lack of need for specialized equipment make it suitable for use outside the clinic. Additional benefits are provided by the use of mobile digital devices (smartphones, pulse oximeters, ECG patches, etc.), which increase the accuracy of data recording, enable automated data collection and transmission to the physician, and improve real-time communication between the patient and the healthcare professional. Thus, 1MSTST is a useful tool for remote assessment of functional capacity, combining accessibility with sufficient clinical information and integrating well into modern models of telemedicine and home telerehabilitation.

Keywords: field test; physical activity; exercise tolerance; telerehabilitation; telemetry.

INTRODUCTION

Telemedicine is a distinct type of digital healthcare service that involves the provision of clinical care remotely, through synchronous or asynchronous interaction between a patient and a healthcare professional, or between healthcare professionals [1]. Throughout the various stages of human development, there has been a constant need for means of communication, which led to the emergence of writing, while messages were exchanged using birds, animals, or messengers – who can be viewed as the precursors of modern courier services. Starting in the second half of the 18th century, industrial revolutions fostered scientific, technical, and economic progress and, naturally, the rapid development of the global healthcare system. The telegraph, telephone, and other means of communication emerged, providing a qualitatively new level of communication and creating the conditions for the development of remote medical technologies. In the modern sense, the origins of telemedicine are usually associated with the use of telephone communication in medical practice. In particular, in the book "The Evolution of Telemedicine across Time", Charles R. Doarn cites one of the first documented examples of remote medical interaction: a clinical case described in 1879 in The Lancet, in which a doctor consulted a mother about her child's health over the telephone [2].

A major impetus for the development of telemedicine stemmed from the need to remotely

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monitor the health of astronauts during space missions. To this end, NASA developed biomedical telemetry systems that enabled the real-time transmission of physiological parameters (information on heart rate, respiration, and other vital signs) to Earth. However, according to Andrew T. Simpson and his co-authors, the development of telemedicine during this period was driven not only by technological innovations but also by political and social factors, particularly the desire to reduce disparities in access to medical care. Specifically, as part of a project for the Tohono O'odham people in Arizona, space-based telemetry and communication solutions were used to provide remote consultations for patients and monitor their condition in remote regions. This made it possible to provide access to specialized medical care without the need to transport patients over long distances [3].

Thus, as early as the 1970s, the basic principles of telemedicine – which are today defined by the World Health Organization (WHO): the provision of medical services at a distance, where geographical remoteness is a determining factor, using information and communication technologies to exchange reliable information for the purposes of diagnosis, treatment, disease prevention, and improving public health [4].

The rapid development and significant transformation of the global healthcare digital landscape were accelerated by pandemic response measures during the 2019 coronavirus disease (COVID-19) pandemic and the additional strain of armed conflicts. The ongoing Russia-Ukraine war has led to catastrophic disruptions in the provision of healthcare services. As of April 2023, a WHO survey found that accessing medical care both within the country and abroad is becoming increasingly difficult due to financial, transportation, time, and other barriers. At the same time, nearly half of those surveyed noted that at least one member of their family has a chronic illness. The most common conditions cited were cardiovascular disease, diabetes, and kidney disease, highlighting the urgent need for uninterrupted access to medical care even in wartime [5].

Despite the proven effectiveness of cardiac rehabilitation, patient participation in such inpatient programs remains low due to a combination of systemic and individual barriers. These include limited access to resources, significant distance to rehabilitation centers, difficulties in organizing regular visits, financial considerations, as well as insufficient patient motivation to change their lifestyle and a lack of proper monitoring of achieved results. The situation is complicated by the limited duration of standard programs without follow-up support, which reduces the sustainability of long-term behavioral changes. Home telerehabilitation is being considered as an alternative; it is based on remote monitoring and allows for the individualization of physical exercise, the rapid transmission of clinical indicators – including electrocardiographic data – and the assessment of the patient's physical and psycho-emotional state. The use of such technologies helps increase treatment adherence through regular feedback, reminders, and clear goal-setting [6].

Despite this, the use of telemedicine in Ukraine remains limited. According to a report by the U.S. Agency for International Development, only about 4.7 % of consultations are conducted using telecommunication tools, such as video conferences, phone calls, text messaging, and other digital communication channels [7]. Under these conditions, it is particularly important to find effective ways to monitor human physiological parameters that do not require expensive and technically complex equipment, yet still provide reliable data on health status.

Robert Ross et al. [8] argue that assessing physiological parameters at rest is insufficient to reflect the body's overall health, and that analyzing the body's response to physical exertion is far more informative, as it requires the coordinated interaction of many bodily systems. Physical activity is defined as any body movement performed by skeletal muscles that requires energy expenditure and, consequently, oxygen consumption. At rest, oxygen consumption is approximately 250 ml/min. During physical exertion, oxygen consumption can increase up to 15-fold. Increased energy consumption by skeletal muscles leads to an increase in lung tidal volume, ventilation rate, gas exchange efficiency, and so on [9]. To meet the increased metabolic demands of tissues, cardiac output increases by at least eight times compared to the resting state. This is achieved through an increase in heart rate (HR), improved cardiac contractility, increased venous return, and vasodilation of blood vessels in the areas involved in physical activity [10].

Thus, a quantitative assessment of cardiorespiratory interaction reflects the level of the body's functional capacity and is a powerful predictor of mortality risk. It encompasses the efficiency of pulmonary ventilation and gas diffusion, systolic and diastolic function of both ventricles, ventricular-arterial coupling, the efficiency of the vascular bed and blood system in ensuring proper redistribution and delivery of oxygen in accordance with the increasing energy demands of tissues, as well as the metabolic activity of skeletal muscles, including their capacity to consume and utilize oxygen and nutrient substrates and to generate afferent regulatory signals to the centers controlling cardiovascular and respiratory activity [8].

Sundeep Chaudhry et al. [11] define cardiopulmonary exercise testing (CPET) as the "gold standard" for assessing cardiorespiratory fitness. Peak oxygen consumption (VO2) during exercise characterizes

the complex mechanism by which the respiratory system meets oxygen demand, its transport by the cardiovascular system, and its utilization by tissues, and allows for the differentiation of cardiac, pulmonary, or peripheral causes of functional impairment for effective personalized treatment [9, 11].

Cardio-pulmonary exercise testing is a universal clinical assessment tool used for a comprehensive analysis of functional status in cardiovascular (coronary artery disease, chronic heart failure, cardiomyopathies, congenital heart defects, pulmonary hypertension), respiratory (chronic obstructive pulmonary disease, bronchial asthma, interstitial lung diseases, cystic fibrosis), and metabolic (obesity, diabetes mellitus, metabolic syndrome) pathologies, as well as in diseases of the musculoskeletal system (myopathies, deconditioning) and peripheral vascular diseases; at the same time, the method is used for preoperative risk stratification, monitoring the effectiveness of rehabilitation measures, and determining the causes of dyspnea of unknown origin [12, 13].

Despite its high diagnostic value, cardiopulmonary exercise testing has a number of significant limitations. In particular, performing CPET requires specialized, expensive equipment (gas analyzers, ergometric systems), standardized conditions, and the involvement of qualified medical personnel, which limits the availability of this diagnostic test, especially in outpatient settings [14]. In addition, the test is relatively lengthy and physically exhausting for the patient, which may complicate its performance in patients with severe functional impairments or comorbidities.

The combination of these factors necessitates the search for and implementation of simpler, more accessible, and safer alternative methods for assessing the body's functional status, which are simultaneously characterized by adequate validity and suitability for remote application.

The aim of the study: to justify the feasibility of using the 1-minute sit-to-stand test for remote assessment of patients' functional capacity, as well as to analyze its clinical informative value and potential for use in home telerehabilitation settings.

MATERIALS AND METHODS

This study was conducted as a narrative review incorporating elements of a systematic analysis of current scientific data, which were retrieved from the electronic scientometric databases PubMed and Web of Science. The analysis included publications from the past 10 years containing data on the validity, reproducibility, sensitivity, and clinical significance of the 1MSTST in patients with cardiorespiratory, metabolic, and other pathologies, as well as studies devoted to the use of the test in telemedicine and home telerehabilitation. During the screening phase, titles and abstracts were analyzed, followed by a full-text evaluation of articles relevant to the review's scope. Exclusion criteria included publications without full text, duplicate publications, conference abstracts without a detailed presentation of results, studies with an insufficiently described or methodologically flawed research base, as well as articles with incomplete or contradictory data. No statistical data analysis was performed within the scope of this study, as the work is of a review nature.

RESULTS AND DISCUSSION

During physical exertion, patients with chronic cardiorespiratory disorders often experience disturbances in the ventilation-perfusion ratio, accompanied by a decrease in the partial pressure of oxygen in arterial blood. The development of arterial hypoxemia limits the ability to perform physical work and leads to a decrease in exercise tolerance. Clinically, this manifests as dyspnea, which reflects metabolic changes and hypoxia-induced cardiorespiratory disturbances. According to Mallikarjuna Korivi and colleagues, the severity of symptoms correlates with the degree of reduced arterial blood oxygenation [9, 15].

Traditionally, patients' functional capacity has been assessed primarily based on their responses to questions regarding daily physical activity, specifically their ability to climb stairs or walk a certain distance without becoming short of breath. This approach relies on self-reporting and does not ensure the objectivity of the results. Consequently, the data obtained may either overestimate or underestimate the actual level of physical endurance [16].

Studies of the interaction between the cardiovascular and respiratory systems under various physiological and pathological conditions have long been the subject of scientific analysis. Igor Malović et al. [17] define physical exercise as an organized, structured, and repetitive form of physical activity aimed at achieving a specific functional outcome that directly modifies cardiorespiratory interaction. At the same time, the coordinated functioning of these systems is maintained even at rest: in particular, the phenomenon of respiratory sinus arrhythmia reflects the physiological variability of the heart rate, in which the heart rate increases during inhalation and decreases during exhalation.

Modern approaches to assessing the cardio-respiratory connection involve not only identifying changes that maintain homeostasis – particularly gas exchange – during physical exertion, but also analyzing the recovery period. The rate and completeness of the return of physiological parameters to baseline levels after the cessation of exertion are decisive. Early post-exercise changes are considered the most informative, as they reflect

the restoration of parasympathetic regulation and the gradual reduction of sympathetic influence. Although recovery is viewed as a process opposite to exercise, its assessment must be based on clear time intervals and the rate of normalization of parameters. A delay in these processes or an insufficient degree of recovery may indicate limited adaptive capacity of the autonomic nervous system or the presence of autonomic dysfunction. This approach has particular diagnostic value in patients who are asymptomatic at rest. In particular, in patients with heart failure and preserved ejection fraction, reduced exercise tolerance is often one of the first objective indicators of functional impairment [10, 17].

It is clear that when selecting the type of physical activity for remote testing, we must take into account the patient's physical capabilities, the availability of technical equipment for both recording the measured parameters and for communication, and, above all, the purpose of the testing – that is, the clinical problem that needs to be addressed. In addition, the results obtained must have high sensitivity and correlate with peak VO2. It is reasonable to choose types of physical activity that do not require special training and correspond to a person's usual daily activities, that is, that replicate real-life conditions as closely as possible. It is precisely these methods of assessing the body's functional state that have come to be known as field tests. As early as the 1960s, walking was proposed as a standardized physical exercise, with the body's functional reserves and ability to adapt to the load analyzed by varying the test duration, distance covered, pace, and gait pattern [16]. Subsequently, among numerous modifications, the 6-minute walk test (6MWT) was identified, characterized by adequate validity, ease of administration, good patient tolerance, and the ability to adequately reflect the level of daily physical activity [18, 19]. However, the use of the 6MWT is also accompanied by a number of limiting conditions. For example, results depend on patient motivation, the adequacy of instruction comprehension, and the learning effect, while standardized administration requires a straight path at least 30 meters long. An additional limiting factor is the risk of falling, especially among elderly patients. The combination of these factors often complicates the use of the method in outpatient settings [20].

Therefore, during the COVID-19 pandemic, the 1-minute sit-to-stand test (1MSTST) became an alternative for both in-person and virtual consultations, in which the physical exertion involved repeated transitions from a sitting to a standing position over a fixed period of time.

To perform the 1MSTST, a chair without armrests with a seat height of approximately 43–46 cm and a timing device (stopwatch, clock, timer) are used; if necessary, a pulse oximeter is used to monitor heart rate (HR) and oxygen saturation (SpO2). Before starting, the patient is instructed on the procedure and shown the technique. The starting position is sitting, with the feet flat on the floor and the arms crossed over the chest to prevent using them for assistance when standing up. It is important to ensure the chair is stable and the environment is safe. For one minute, the patient performs as many full transitions as possible from a standing to a sitting position (standing up and sitting down), maintaining their own pace and without using their hands. During the test, the number of repetitions performed is recorded, and, if possible, changes in clinical symptoms (shortness of breath, fatigue) and the dynamics of hemodynamic parameters and oxygen saturation are assessed. After the test is completed, exercise tolerance is analyzed; if necessary, monitoring continues during the recovery period, which allows for a comprehensive assessment of the patient's functional status and the nature of their response to submaximal physical exertion [20, 21].

The number of full sit-to-stand repetitions performed in one minute is the primary outcome of the 1MSTST. Additionally, it is advisable to record blood oxygen saturation, changes in heart rate, blood pressure (BP), as well as subjective assessments of exertion, shortness of breath, and fatigue using the Borg scale. The method does not require complex, expensive equipment, is easily reproducible under various conditions, and is highly standardized, ensuring its practical suitability for clinical use [19, 21].

With the advent of affordable personal digital devices, such as mobile phones and smartwatches, accelerometers or GPS technology can be used to analyze results. This allows patients to independently conduct field tests in their familiar surroundings and at a time that is convenient for them. For convenience, special interactive apps can be installed on personal mobile phones or other devices—that is, those with which patients are already familiar. This allows for the additional recording of data on spontaneous physical activity collected by the phone's sensors or any wearable gadget connected to it [22].

Improvements to the classic 1STST through the integration of biomechanical sensors aim to increase the objectivity, scope, and clinical relevance of the results obtained, not only for monitoring the progression of neuromuscular, cardiorespiratory, and other diseases, but also for tracking age-related declines in physical activity. The range of auxiliary systems is rapidly expanding, and it is already possible to measure heart rate and heart rate variability (HRV) [23]. Some systems include a cardiac patch for ECG, a portable cuff for measuring blood pressure, and/or a respiratory monitor [24]. As a result, telemetry (mHealth) is rapidly developing—a set of technologies

and tools that ensure continuous data collection (remote measurement), real-time interpretation, and transmission of information to the physician. Some digital platforms allow for the processing of results from multiple patients, offer capabilities for retrospective analysis, and utilize PACS (Picture Archiving and Communication System), i.e., a service for the collection, transmission, storage, and processing of images, etc. It is clear that the implementation of the capabilities offered by the industry requires sustainable funding, regulatory frameworks, training for healthcare professionals, and, of course, appropriate technological infrastructure [25].

Remote monitoring of physical activity at home involves the step-by-step collection of data (questionnaires, heart rate, blood pressure, SpO2, ECG readings, etc.) before, during, and after the activity, followed by the transmission of this information to the monitoring center (Fig.). Data transmission can occur in three modes: synchronous, which provides continuous real-time monitoring of parameters; asynchronous, which involves accumulating information for later transmission and delayed analysis; and remote monitoring mode, designed for long-term observation of the patient's condition. Practical application is most often based on a combination of these approaches, which allows for simultaneous monitoring of exercise safety, analysis of parameter dynamics, and, if necessary, timely remote adjustment of the rehabilitation program [2, 6].

When administering functional capacity tests remotely, significant challenges arise regarding the verification of proper performance and the objectivity of data recording. In a study by Simin Xie et al., an approach to overcoming these challenges was proposed by developing and validating a machine learning model in patients with COPD based on the use of built-in smartphone sensors. Specifically, an accelerometer and a gyroscope were used to record physical activity, and their signals were analyzed to identify "sit-stand" cycles. The peak and minimum values of the accelerometer signals underwent preliminary screening, which allowed for the precise determination of transition points between movement phases and the quantitative assessment of the number of repetitions. This approach minimizes the influence of subjective errors characteristic of self-counting or visual monitoring. Additionally, the algorithm accounted for patients' individual clinical characteristics, ensuring more accurate modeling of functional exercise tolerance. The resulting digital parameters were used to construct a predictive model of 6MWT distance, which demonstrated high agreement with actual values. Thus, the integration of smartphone sensor data with machine learning methods allows for increased objectivity in remote testing, standardizes the assessment of the 1-minute sit-to-stand test, and expands its application in the telemedical management of patients with COPD [20].

Md Rafi Islam et al. set out to develop a device capable of continuously monitoring physical activity in real-life settings. The system they proposed combines inertial sensors (an accelerometer and a gyroscope), which record the trajectory and velocity characteristics of foot movement, with a strain gauge integrated into the shoe laces, which detects changes

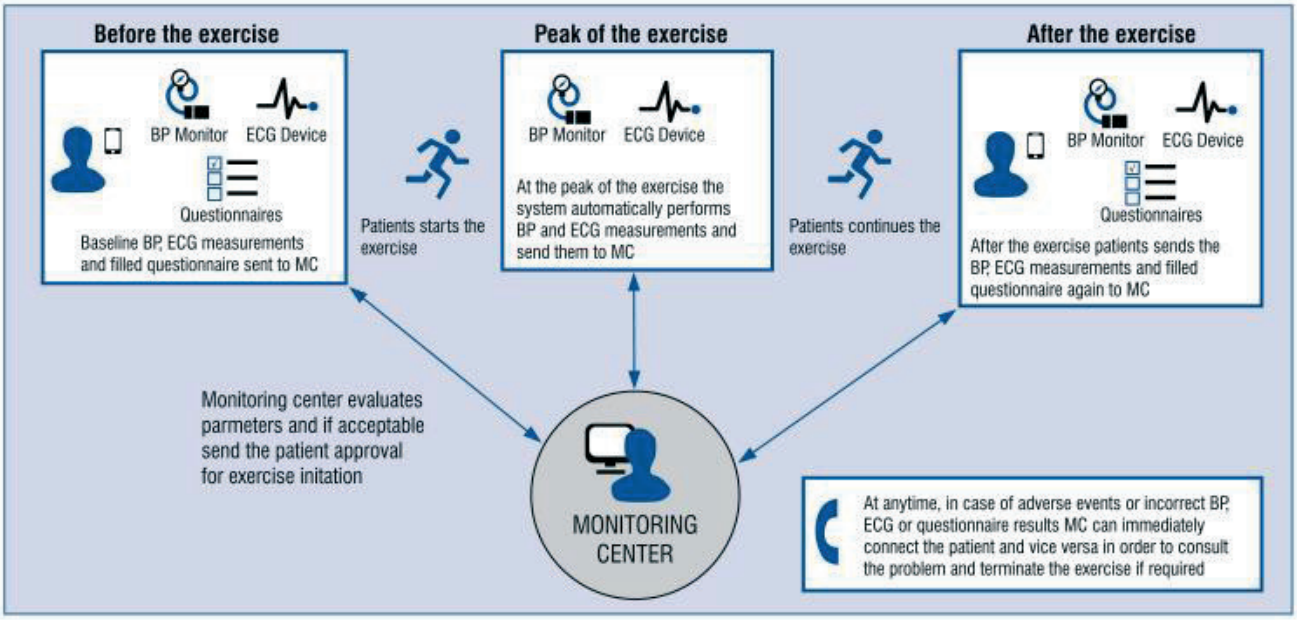

Fig. Concept and design of home training utilizing telemonitoring technology: BP – blood pressure; ECG – electrocardiogram; MC – Monitoring Center [6].

in their tension. The signals obtained reflect the redistribution of mechanical load during the initiation of the transition from a sitting to a standing position. The integration of these data sources enables not only the quantitative counting of standing-up events but also the determination of their duration, which is clinically significant as an indicator of lower limb muscle strength and the functional state of the musculoskeletal system for assessing the risk of falls. The compactness and autonomy of the sensor system allow for its use in everyday living conditions without significantly affecting the user's behavioral patterns, which, in turn, enhances the ecological validity of the results obtained. Given that postural stability during movement is a key prerequisite for maintaining independence, especially in elderly patients, such indicators can be considered objective markers of the level of daily physical activity [26].

The 1-minute sit-to-stand test plays a crucial role in assessing a person's functional status, prognosis, and disease outcomes, as well as in monitoring the effectiveness of treatment and rehabilitation measures for virtually all chronic respiratory diseases and many cardiovascular conditions. It allows for the assessment of a patient's functional status without the need for the complex and expensive equipment required for cardiorespiratory stress testing, as well as in patients for whom such testing is contraindicated. Remote monitoring facilitates the early detection of changes and the prompt adjustment of treatment measures, reducing the number of hospitalizations and emergency visits [27]. In cases of chronic lung diseases (e.g., COPD, interstitial lung diseases), remote monitoring (using pulse oximeters, wearable devices, and smartphone apps) enables improved self-management, timely detection of exacerbations, and reduced burden on inpatient services [20, 28].

The scope of application of the 1-minute sit-to-stand test has long extended beyond the cardiopulmonary field. The simplicity of the test allows for a non-specific, comprehensive assessment of many systems involved in physical activity. In particular, its results can help determine the degree of functional impairment in neuromuscular diseases [29], chronic fatigue, post-viral asthenia syndrome, post-COVID-19 recovery, in frail older adults [20, 30], and other conditions.

CONCLUSSIONS

It has been established that the 1-minute sit-to-stand test (1MSTST) is a simple, safe, and accessible tool for assessing functional capacity that does not require specialized equipment and can be performed in an outpatient setting. It has been demonstrated that the 1MSTST has adequate clinical utility and can be used as an alternative to more complex or resource-intensive methods, such as exercise cardiopulmonary testing or the 6-minute walk test. It has been shown that the test allows for the objective assessment of exercise tolerance by evaluating the integrated response of the cardiorespiratory system, not only during exercise but also during the recovery period, which enhances the diagnostic value of the test and enables the detection of early signs of impaired adaptive mechanisms. It is emphasized that the use of the 1-minute sit-to-stand test in a telemedicine format contributes to increased access to medical care, ensures continuous monitoring of patients' condition, and can be effectively integrated into home telerehabilitation programs.

Thus, the implementation of the 1MSTST into clinical practice and remote monitoring models is a feasible and promising direction, especially in the context of limited access to medical resources and the growing need for personalized patient care.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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1-хвилинний тест «сісти-встати»: простий інструмент для дистанційної оцінки функціональної здатності в епоху телемедицини

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Анотація. Сучасні виклики системи охорони здоров'я, зокрема пандемія COVID-19 та воєнні дії, зумовлюють необхідність розширення можливостей дистанційного надання медичної допомоги. Телемедицина створює нові можливості для спостереження за станом пацієнтів, однак вимагає впровадження простих, валідних і доступних інструментів оцінки функціонального стану, придатних для використання в домашніх умовах. Саме тому метою дослідження було обґрунтувати доцільність використання 1-хвилинного тесту «сісти-встати» (1MSTST) для дистанційної оцінки функціональної здатності, а також проаналізувати його клінічну інформативність й можливості використання в позагоспітальній телереабілітації. Роботу виконано у форматі аналітичного огляду наукових джерел із систематизацією даних, відібраних у базах PubMed та Web of Science за останні 10 років. Узагальнення результатів свідчить, що оцінка кардіореспіраторної взаємодії під час фізичного навантаження та у відновному періоді є більш інформативною, ніж аналіз показників у спокої; водночас референтним методом залишається кардіопульмональне тестування з фізичним навантаженням, застосування якого обмежене складністю, потребою у спеціалізованому обладнанні, високими ресурсними витратами тощо. Тест 6-хвилинний ходьби частково долає ці обмеження, однак не завжди придатний для дистанційного використання. На цьому тлі 1MSTST вирізняється практичною доцільністю: він дозволяє кількісно визначити толерантність до навантаження, оцінити кардіореспіраторну відповідь під час виконання тесту та у фазі відновлення, а також виявити ознаки зниження фізичної працездатності у пацієнтів. Простота виконання та відсутність потреби у спеціальному обладнанні забезпечують можливість його застосування поза клінікою. Додаткові переваги створює використання мобільних цифрових пристроїв (смартфонів, пульсоксиметрів, кардіологічних патчей для ЕКГ тощо), які підвищують точність фіксації показників, забезпечують їх автоматизовану реєстрацію та передачу лікарю, а також покращують комунікацію між пацієнтом і медичним фахівцем у режимі реального часу. Таким чином, 1MSTST є доцільним інструментом для дистанційної оцінки функціональної здатності, який поєднує доступність із достатньою клінічною інформативністю та добре інтегрується у сучасні моделі телемедицини і домашньої телереабілітації.

Ключові слова: польовий тест; фізична активність; толерантність до фізичного навантаження; телереабілітація; телеметрія.

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Central hemodynamic parameters in girls and boys with different body types

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Abstract. The somatotypological determination of central hemodynamic parameters is of significant importance for predicting susceptibility to and the course of cardiovascular diseases, as well as athletic performance. However, there is a lack of information on the somatotypological status of hemodynamic parameters in otherwise healthy individuals, which could serve as baseline values for comparison in clinical studies of various types. The aim of the study was to establish the somatotypological characteristics of central hemodynamic parameters, determined using tetrapolar rheovasography, in healthy urban adolescents residing in the Podillia region of Ukraine. Anthropometric, somatotypological, and rheographic studies were conducted on 168 healthy young men (aged 17 to 21) and 167 healthy young women (aged 16 to 20) who have resided in the Podillia region of Ukraine for three generations. Somatotyping was performed according to Heath-Carter, whereby the girls were divided into 6 groups: endomorphs (n=11), mesomorphs (n=40), ectomorphs (n=38), ecto-mesomorphs (n=20), endo-mesomorphs (n=25), girls with an intermediate somatotype (n=33), and the boys into 5 groups: mesomorphs (n=69), ectomorphs (n=25), ecto-mesomorphs (n=30), endo-mesomorphs (n=11); boys with an intermediate somatotype (n=20). The analysis of the results was performed using the STATISTICA 5.5 software. The study identified constitutional differences in central hemodynamic parameters; specifically, among ecto-mesomorphic girls, stroke volume, cardiac output, stroke index, cardiac index, left ventricular ejection fraction, and left ventricular power were the highest, while in endo-

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mesomorphs, most of these parameters had the lowest values. Specific and total peripheral resistance were highest in endomorph girls, while these parameters were lowest in endo-mesomorphs. Among mesomorphic boys, the highest values of blood pressure, stroke volume, left ventricular power, and energy expenditure were found, while ectomorphs had the lowest values for these parameters. In boys of certain somatotypes, central hemodynamic parameters were significantly higher than in girls. Individuals with ectomorphic and ecto-mesomorphic somatotypes showed no gender differences in specific central hemodynamic parameters. The central hemodynamic parameters we determined can be considered as baseline normative values.

Keywords: central hemodynamics; tetrapolar rheography; somatotype; adolescent age; sexual dimorphism.

INTRODUCTION

An integral characteristic of a person's somatic status is their constitution or somatotype, and according to D. S. Avabde et al. [1], the use of a constitutional approach in studying the morpho-functional indicators of individual body systems is appropriate and promising. This is confirmed by the works of other authors, who note that constitution is a multidimensional, integrative, and comprehensive characteristic of a person that is closely interrelated with their state of health [2, 3]. Researchers, notably A. Cowie et al. [4] and X. Liang et al. [5], have demonstrated that there is an interdependent relationship between constitutional features of external body structure and susceptibility to and the course of cardiovascular diseases. Y. Wang et al. [6] note that human constitution must be considered from the perspective of internal metabolism and resistance to external pathogenic factors. They demonstrated the existence of links between human constitution and cardiovascular diseases and linked constitutional characteristics to lifestyle and the risk of developing cardiovascular diseases. In studies by S. Singh et al. [7], correlations were found between the onset and course of hypertension in Indian residents and body mass index, waist and hip circumferences, and type of obesity, and it was demonstrated that abdominal obesity was directly proportional to high blood pressure. The authors attribute the development of hypertension in obese individuals to the fact that an increase in body weight leads to an increase in stroke volume and, simultaneously, in peripheral resistance in the arterioles [7].

For modern scientists, the existence of correlations between specific parameters of body conformation and cardiovascular system indicators is undisputed [8]. O.P. Khatitskaya studied the characteristics of peripheral hemodynamic parameters in the thigh and lower leg among male athletes of various somatotypes who specialized in track and field, volleyball, and wrestling [9]. In general, the issue of somatotypological determinants of cardiovascular system parameters is raised in sports medicine practice, which is of significant importance for athletic performance, since the parameters of this particular system are capable of significant variation depending on the specifics of the sport and the athlete's constitutional characteristics [10–12].

However, there is a lack of information on the somatotypological status of hemodynamic parameters in otherwise healthy individuals, which could serve as baseline values for comparison in clinical studies of various kinds. Thus, the need to establish modern reference ranges for rheocardiographic parameters in healthy young women and men of the Ukrainian ethnic group and to address the issue of the characteristics of central hemodynamic parameters in individuals with a specific somatotype determines the relevance of this study.

The aim of the study: to establish the somatotypological characteristics of central hemodynamic parameters, determined using tetrapolar rheovasography, in essentially healthy urban adolescents residing in the Podillia region of Ukraine.

MATERIALS AND METHODS

Following a preliminary questionnaire regarding any history of medical conditions, we conducted a comprehensive examination of 247 young men aged 17 to 21 and 235 young women aged 16 to 20. All of them were urban residents of the Ukrainian ethnic group who are third-generation residents of the Podillia region of Ukraine. Young men and women in whom any medical conditions were detected were excluded from the group of healthy individuals. Thus, the group of practically healthy individuals consisted of 168 young men and 167 young women. Rheographic parameters were determined using a computerized diagnostic system capable of simultaneously recording an electrocardiogram, phonocardiogram, basic and differential tetrapolar rheogram, and measuring blood pressure. The portable multifunctional device was developed by staff at VNTU and the Research Center of the M. I. Pirogov Vinnitsa National Medical University. Somatotyping was performed using a modified version of the Heath-Carter method [13]. After determining the somatotypes, the girls were divided into 6 somatotypological groups: endomorphs (n=11), mesomorphs (n=40), ectomorphs (n=38), ecto-mesomorphs (n=20), endo-mesomorphs (n=25), girls with an intermediate somatotype (n=33); the boys were divided into 5 groups: mesomorphs (n=69), ectomorphs (n=25), ecto-mesomorphs (n=30), endo-mesomorphs (n=11); boys with an intermediate somatotype (n=20).

The results were analyzed using STATISTICA 5.5 (license No. AXXR910A374605FA) with nonparametric methods for evaluating the indicators. Differences between the compared samples were determined using the Mann-Whitney U test (when assessing somatotypological and gender differences between girls and boys of a specific somatotype).

The Bioethics Committee of the M. I. Pirogov Vinnitsa National Medical University determined that this study does not violate fundamental bioethical norms (Protocol No. 1 dated January 31, 2021).

RESULTS AND DISCUSSION

We found that there were no statistically significant differences in systolic blood pressure readings among adolescent girls belonging to different somatotypes. Among adolescent boys, the highest values of this indicator were recorded in the mesomorph group, and the lowest in the ectomorph group. A significant difference in systolic blood pressure was found among adolescent boys with these somatotypes ($p<0.05$).

When comparing systolic blood pressure values between girls and boys belonging to the same somatotype group, we found statistically significant gender differences in all groups. In boys, this indicator was statistically significantly higher compared to adolescent females (Table).

There were no significant differences in diastolic and mean arterial pressure values among girls with different somatotypes. In mesomorphic boys, these indicators were statistically significantly higher than in boys with an ectomorphic somatotype. Among other groups of adolescent boys, the somatic differences were not significant.

We found statistically significant gender differences in diastolic blood pressure when comparing adolescents with mesomorphic and ecto-mesomorphic somatotypes. In individuals with an endo-mesomorphic body type,

Table. Gender differences in indicators of central hemodynamics in young people with different somatotypes (M±σ)

Indicators	Somatotype	Girls	Boys	p
Systolic blood pressure (mmHg)	mesomorphic	117,8±12,2	129,3±12,9	**<0,001**
	ectomorphic	114,1±11,1	122,4±13,4	**<0,05**
	ecto-mesomorphic	116,0±11,9	124,9±13,6	**<0,05**
	endo-mesomorphic	113,2±11,7	126,0± 8,6	**<0,01**
	intermediate	116,9±9,7	125,5±11,3	**<0,05**
Diastolic blood pressure (mmHg	mesomorphic	72,27±10,7	79,92±8,9	**<0,001**
	ectomorphic	71,80±8,01	74,16±11,22	>0,05
	ecto-mesomorphic	70,50±10,18	77,32±11,48	**<0,05**
	endo-mesomorphic	69,32±10,98	77,30±8,65	**=0,057**
	intermediate	72,29±6,30	76,16±6,52	>0,05
Average blood pressure (mmHg)	mesomorphic	87,15±9,50	96,03±8,86	**<0,001**
	ectomorphic	85,52±8,48	89,88±11,24	>0,05
	ecto-mesomorphic	85,40±9,99	92,87±11,37	**<0,05**
	endo-mesomorphic	83,60±10,50	93,3±8,0	**<0,05**
	intermediate	86,90±6,57	92,22±7,06	**<0,05**
Stroke blood volume (ml)	mesomorphic	73,81±23,36	94,30±21,08	**<0,001**
	ectomorphic	69,77±19,11	84,46±20,10	**<0,01**
	ecto-mesomorphic	82,48±23,58	89,75±21,88	>0,05
	endo-mesomorphic	62,03±14,41	96,01±20,84	**<0,001**
	intermediate	71,23±19,97	88,40±19,40	**<0,01**
Minute blood volume (l)	mesomorphic	4,860±1,684	5,134±0,969	**<0,05**
	ectomorphic	4,622±1,359	4,969±1,314	>0,05
	ecto-mesomorphic	5,243±1,479	5,261±1,267	>0,05
	endo-mesomorphic	4,171±0,872	5,427±1,126	**<0,01**
	intermediate	4,382±1,000	5,157±1,01	**<0,05**
Impact index (ml/m^2)	mesomorphic	45,17±13,64	50,28±11,18	**<0,01**
	ectomorphic	44,50±12,03	46,68±11,11	>0,05
	ecto-mesomorphic	51,80±13,10	49,12±13,01	>0,05
	endo-mesomorphic	38,72±10,13	49,20±10,65	**<0,05**
	intermediate	43,80±11,51	46,27±9,34	>0,05
Cardiac index (l/min/m^2)	mesomorphic	3,002±0,943	2,766±0,522	>0,05
	ectomorphic	2,981±0,862	2,789±0,792	>0,05
	ecto-mesomorphic	3,322±0,838	2,905±0,745	>0,05
	endo-mesomorphic	2,632±0,603	2,807±0,572	>0,05
	intermediate	2,734±0,572	2,726±0,454	>0,05

Continuation of the table

Indicators	Somatotype	Girls	Boys	p
Specific peripheral resistance (Dyn/s/cm-5)	mesomorphic	31,41±8,87	35,99±8,00	**<0,001**
	ectomorphic	30,95±9,22	34,72±10,61	>0,05
	ecto-mesomorphic	26,98±6,19	33,73±9,01	>0,05
	endo-mesomorphic	33,22±8,14	34,32±6,77	>0,05
	intermediate	33,46±9,34	34,45±4,49	>0,05
Total peripheral resistance (Dyn/s/cm-5)	mesomorphic	1569,9±457,7	1552,9±351,4	>0,05
	ectomorphic	1589,3±447,3	1544,3±441,3	>0,05
	ecto-mesomorphic	1385,5±351,4	1480,7±377,9	>0,05
	endo-mesomorphic	1662,2±367,1	1418,9±269,6	>0,05
	intermediate	1682,0±491,7	1470,8±240,5	>0,05
Volumetric speed of movement (ml/s)	mesomorphic	271,3±85,6	352,4±73,0	**<0,001**
	ectomorphic	258,9±65,1	322,9±71,1	**<0,01**
	ecto-mesomorphic	294,9±81,80	336,7±72,7	>0,05
	endo-mesomorphic	229,8±50,4	360,5±68,3	**<0,001**
	intermediate	258,0±65,7	331,8±68,5	**<0,001**
Left ventricular power (W)	mesomorphic	3,152±1,031	4,508±1,017	**<0,001**
	ectomorphic	2,956±0,845	3,866±0,981	**<0,001**
	ecto-mesomorphic	3,375±1,083	4,190±1,170	**<0,05**
	endo-mesomorphic	2,574±0,702	4,489±0,954	**<0,001**
	intermediate	2,988±0,799	4,110±1,045	**<0,001**
Energy consumption (W/l)	mesomorphic	0,195±0,021	0,216±0,021	**<0,001**
	ectomorphic	0,191±0,019	0,201±0,028	**<0,05**
	ecto-mesomorphic	0,189±0,021	0,209±0,026	**<0,05**
	endo-mesomorphic	0,185±0,024	0,215±0,018	**<0,01**
	intermediate	0,192±0,013	0,211±0,024	<0,01

Note: p is an indicator of statistically significant difference between girls and boys with the same somatotype.

the increase in diastolic blood pressure among boys was a trend (p=0.051). Mean arterial pressure showed no significant gender differences only in individuals with an ectomorphic body type; in adolescent males of other somatotypes, this indicator was statistically significantly higher than in females. It is noteworthy that the most pronounced gender differences in all types of blood pressure are observed in individuals with a mesomorphic body type (see Table).

Stroke volume was highest in girls with an ecto-mesomorphic body type, while the lowest value for this parameter was observed in endo-mesomorphs. Girls with an ecto-mesomorphic somatotype had a significantly higher stroke volume than girls with endo-mesomorphic (p<0.01) and ectomorphic (p<0.05) somatotypes. Meso-morphic girls also had a statistically significant (p<0.05) higher value of this indicator than endo-meso-morphic girls. Boys with a mesomorphic somatotype had a significantly higher (p<0.05) stroke volume than boys with ectomorphic and ecto-mesomorphic somatotypes.

We found that stroke volume was significantly higher in boys with mesomorphic, endo-mesomorphic, ectomorphic, and intermediate somatotypes than in girls of the corresponding constitutional types (see Table).

Minute blood volume was significantly higher in girls with an ecto-mesomorphic somatotype compared to those with an endo-mesomorphic type (p<0.05); among other somatic groups of adolescent females, the difference was not significant. In adolescent males with different somatotypes, this indicator was nearly at the same level, and there were no significant differences. It is noteworthy that the most pronounced sex differences in the magnitude of all types of blood pressure are observed in individuals with a mesomorphic somatotype (see Table).

It was found that the impact index differed significantly between girls with different types of body structure. The highest values were found in girls with ecto-mesomorphic somatotype, the lowest – with endo-mesomorphic and endomorphic. Ecto-mesomorph girls had a significantly higher given parameter than females with endomorphic, mesomorphic, intermediate intermediate (in all cases p<0.05) and endo-mesomorphic (p<0.001) somatotypes, and between ecto-mesomorph and ectomorph girls this feature remained in the form of a trend (p=0.057). In addition, it was established that females with ectomorphic and mesomorphic somatotypes had higher shock index values (p<0.05) than girls with endo-mesomorphic type, and between the latter and girls with an average balanced type, this pattern also had the appearance of a trend. We found no significant differences in the value of the impact index in young men of different constitutional types. It

was established that only boys with mesomorphic and endo-mesomorphic somatotypes have this indicator significantly higher than girls of the corresponding somatic groups (see Table).

The cardiac index value was the highest in girls with ecto-mesomorphic somatotype, significant differences were established between them and girls with endomorphic ($p<0.01$), endo-mesomorphic ($p<0.01$) and average intermediate somatotypes ($p<0.05$). This indicator was the lowest in endomorph girls, and the highest in mesomorphs, the differences between these groups were not significant when compared at $p=0.055$. In adolescent boys of different somatic groups, there was no significant difference in the value of this parameter.

The cardiac index between the groups of girls and boys of a particular somatotype had no significant gender difference (see Table).

The highest specific peripheral resistance was found in girls with an endomorphic type of body structure, the smallest – with an ecto-mesomorphic somatotype, a significant difference was established between these groups ($p<0.01$), in addition, a statistically significant decrease in this indicator was noted in ecto-mesomorphs compared to endo-mesomorphs ($p<0.05$) and girls with an average intermediate somatotype ($p<0.01$), relative to girls with a mesomorphic somatotype, this feature can be traced in the form of a trend. In adolescent boys of different somatotypes, there are no significant differences in the value of this indicator. We established reliable gender differences in the value of the specific peripheral resistance only in one group – in persons with mesomorphic somatotype, it is greater in boys ($p<0.001$) than in girls (see Table).

Girls with an ecto-mesomorphic somatotype had the lowest total peripheral resistance, a significant difference was established between them and endo-mesomorphs ($p<0.05$) and girls with an average intermediate somatotype ($p<0.05$).In adolescent boys of different somatotypes, there are no significant differences in the value of this indicator. We did not establish reliable gender differences in total peripheral resistance in all somatotypological groups (see Table).

We found that only girls with an endo-mesomorphic somatotype had a significantly lower volumetric velocity of blood movement compared to girls with mesomorphs ($p<0.05$) and ecto-mesomorphs ($p<0.01$). In adolescent boys of different somatic groups, there is no significant difference in the value of this parameter.

The volumetric speed of blood movement had pronounced gender somatotypological differences, in almost all somatic groups this indicator was significantly higher in boys, only in girls and boys with ecto-mesomorphic somatotype there were no statistically significant differences (see Table).

The power of the left ventricle was the smallest in girls with an endo-mesomorphic somatotype, significant differences were established between them and mesomorph ($p<0.05$) and ecto-mesomorph ($p<0.01$) girls. It was established that boys with a mesomorphic somatotype have significantly greater left ventricular power than boys with an ectomorphic somatotype ($p<0.01$). This indicator is characterized by pronounced sexual dimorphism with a predominance of values in boys in all somatotypological groups (see Table).

Indicators of energy expenditure in girls of different somatotypes did not differ statistically significantly. In young men with a mesomorphic type of body structure, this indicator is significantly higher than in boys with ectomorphs ($p<0.01$) and ecto-mesomorphs ($p<0.05$).We have established that male persons with any somatotype have statistically significantly higher energy expenditure than female representatives of the corresponding constitutional type (see Table).

Thus, the variability of the parameters of central hemodynamics is affected by the morpho-functional features of the body structure, which can be attributed to the morphological constitution of a person, i.e., his somatotype [14–16], because in our study it was found that in adolescent girls, most indicators of central hemodynamics, with the exception of blood pressure and energy expenditure, are reliably different in individuals with different types of body structure. We found that girls with an ecto-mesomorphic somatotype had the highest values of stroke and minute blood volumes, stroke and heart indices, volumetric speed of movement and power of the left ventricle compared to the indicators of persons of other somatotypes; the smallest value above the listed indicators, with the exception of the cardiac index, was established by us in the group of girls with endo-mesomorphic somatotype. Specific and total peripheral resistance are the highest in endomorph girls, in females with an ecto-mesomorphic somatotype, these indicators have statistically significantly lower values compared to girls of other constitutional groups. Studying the parameters of central hemodynamics in volleyball players of a high level of skill, it was found that compared to non-athletes of the same age, stroke and minute blood volumes, stroke index, volume velocity, and left ventricular power were statistically significantly higher in them [17].

Most of the indicators of central hemodynamics, determined by us using the method of tetrapolar reocardiography, did not have reliable somatotypological differences in adolescent boys.The highest values of blood pressure, stroke volume, left ventricular power and energy expenditure were found in boys with mesomorphic somatotype, the lowest in ectomorph boys. The fact that these indicators did not reliably differ between young men with other constitutional types also attracts attention.

Scientists drew attention to the fact that representatives of certain somatotypes, even within the same sport, have differences in the indicators of the cardiovascular system. Thus, changes in indicators of heart rate variability were found in mesomorphic somatotype track and field athletes compared to young men of the same constitutional type who did not play sports [10] and mesomorphic volleyball players compared to mesomorphic somatotype non-athletes [11].

In addition, it was established that the following electrocardiographic parameters were significantly higher in young male athletes who belonged to the mesomorphic somatotype, compared to athletes of other somatotypes: the duration of the P wave, the QT and RR intervals, as well as the amplitude of the P, R, T waves [18]. Scientific studies have proven that in individuals with a preference for the expression of the mesomorphic component of the somatotype, most of the mofro-functional indicators of central [19] and peripheral [20] hemodynamics had either a tendency to higher values or were significantly higher compared to representatives of other somatotypes. In the study of P. V. Sarafynyuk and I. D. Kuhar [21] it was found that practically healthy teenagers of the mesomorphic somatotype of the Podil region of Ukraine had the highest values of echocardiographic parameters of the heart.So, the reliable predominance of rheovasographic parameters of central hemodynamics in practically healthy young boys with mesomorphic somatotype revealed in our study is well-founded, confirmed by numerous scientific works of this direction.

The use of the somatotypological approach in this work confirmed the presence of sexual dimorphism in the value of central hemodynamic parameters [22, 23]. Comparison of systolic, diastolic, and average blood pressure, stroke volume, volumetric velocity of blood movement, left ventricular power, and energy expenditure between adolescent girls and boys who belonged to a certain somatotype made it possible to conclude that the values of diastolic and average arterial pressures and minute blood volume do not have reliable gender differences in individuals with an ectomorphic somatotype. and stroke and minute volumes and volume speed of blood movement do not reliably differ in individuals with ecto-mesomorphic somatotype. We can assume that an increase in the value of the ectomorphic component of the somatotype, which reflects the relative linearity or elongation of the body, eliminates gender differences in individual indicators of central hemodynamics.

The need for constant control of the functional state of the cardiovascular system is emphasized in their studies by D. Berhtraum et al. [24] and T. Shevchuk et al. [25], emphasizing the significance of the updated regulations

Thus, the detection of hemodynamic heterogeneity in people with different body types requires the latest constitutional approaches to the assessment and interpretation of the obtained results of central hemodynamic indicators.

CONCLUSIONS

Somatotypological regularities of changes in central hemodynamic parameters, obtained by the method of tetrapolar reocardiography, in practically healthy urban youth of the Podilsk region of Ukraine, taking into account the factor of sexual determinism, were established. It was established that the vast majority of indicators of central hemodynamics in youth have pronounced somatotypological differences. They differ the most in girls with endo-mesomorphic, ecto-mesomorphic, endomorphic somatotypes. In ecto-mesomorph girls, stroke and minute volumes of blood, stroke and cardiac indices, volume speed of movement and power of the left ventricle have the greatest values; the lowest value was established in the group of girls with endo-mesomorphic somatotype. The indicators of specific and total peripheral resistance are the highest in endomorph girls, the lowest in girls with an ecto-mesomorphic somatotype. Compared to other constitutional groups, boys with a mesomorphic somatotype had the highest blood pressure, stroke volume, left ventricular power, and energy expenditure, while boys with an ectomorphic somatotype had the lowest values of these parameters.

It was established that in practically healthy urban young men of certain somatotypes, most indicators of central hemodynamics are reliably higher than in girls. Exceptions are only individuals with ectomorphic and ecto-mesomorphic somatotypes, in which there are no gender differences in individual indicators of central hemodynamics (diastolic, mean arterial pressure, minute and stroke volume of blood, volume velocity of blood movement).

Our application of the somatotypological approach to the study of normative rheographic parameters of central hemodynamics will allow us to improve the criteria for a more precise distinction between normality and pathology, which in turn will make it possible to more precisely approach the issue of early detection of risk groups and predict diseases of the organs of the cardiovascular system.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Показники центральної гемодинаміки у дівчат і юнаків із різними соматотипами

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Анотація. Соматотипологічна зумовленість показників центральної гемодинаміки має вагоме значення для прогнозування схильності та перебігу захворювань серцево-судинної системи, а також спортивних досягнень. Але відчувається недостатність інформації про соматотипологічний стан гемодинамічних показників у практично здорових осіб, які можна використати як базові значення для порівняння у клінічних дослідженнях різного спрямування. Метою роботи було встановлення соматотипологічних особливостей показників центральної гемодинаміки, визначених за допомогою тетраполярної реовазографії, у практично здорових міських осіб юнацького віку – мешканців Подільського регіону України. Було проведено антропометричне, соматотипологічне та реографічне дослідження практично здорових 168 юнаків (віком від 17 до 21 року) і 167 дівчат (від 16 до 20 років), які у третьому поколінні проживають на території Подільського регіону України. Соматотипування проводили за Heath-Carter, за яким дівчат поділили на 6 груп: ендоморфи (n=11), мезоморфи (n=40), ектоморфи (n=38), екто-мезоморфи (n=20), ендо-мезоморфи (n=25), дівчата із середнім проміжним соматотипом (n=33). Юнаків теж поділили на 5 груп: мезоморфи (n=69), ектоморфи (n=25), екто-мезоморфи (n=30), ендо-мезоморфи (n=11); хлопці із середнім проміжним соматотипом (n=20). Проаналізували отримані результати за допомогою програми STATISTICA 5.5. Встановлені конституціональні особливості параметрів центральної гемодинаміки, зокрема у дівчат-екто-мезоморфів ударний і хвилинний об'єми крові, ударний та серцевий індекси, об'ємна швидкість руху та потужність лівого шлуночка мали найвищі значення, а в ендо-мезоморфів величина більшості даних показників мала найменші значення. Питомий і загальний периферичний опір були найбільшими в дівчат-ендоморфів, у ендо-мезоморфів дані показники найменші. В юнаків-мезоморфів виявлено найбільшу величину артеріального тиску, ударного об'єму, потужності лівого шлуночка та витрат енергії, а в ектоморфів були найменші значення даних показників. У юнаків окремих соматотипів параметри центральної гемодинаміки достовірно вищі, ніж у дівчат. Особи з ектоморфним та екто-мезоморфним соматотипами не мали статевих відмінностей між окремими показниками центральної гемодинаміки, які можна розглядати як базові нормативні значення.

Ключові слова: центральна гемодинаміка; тетраполярна реогрфія; соматотип; юнацький вік; статевий диморфізм.

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Influence of iodine deficiency state and influence of strumogenic products on organs of the cardiovascular system

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Abstract. Currently, iodine deficiency diseases are a global medical and social problem: according to the WHO, various health disorders caused by iodine deficiency rank third among the 38 most common non-infectious diseases. The frequency of damage to the organs of the cardiovascular system and the prevalence of iodine deficiency is a prerequisite for studying the effect of thyroid imbalance on the heart and blood vessels. The goal was to follow the morphofunctional changes in the endocardium and the wall of arteries of different types in the dynamics of iodine deficiency development in postnatal ontogeny. The work was performed on experimental animals of sexually immature and sexually mature age. Achieving a state of iodine deficiency is confirmed by ioduria indicators and a thyroid profile. Both on the 60th day and on the 90th day of the iodine deficiency state, edematous changes occur in the connective tissue components, in the wall of blood vessels, especially in the endothelial layer, in all the examined organs, which was confirmed by light-optical and electron microscopic research methods. Thus, the available data allow us to consider iodine deficiency as a systemic factor that can affect the cardiovascular system due to thyroid dysfunction. The combined intake of current-generating substances can increase this effect, especially if iodine deficiency has already formed.

Keywords: experiment; rats; heart; arteries; metabolic disorders; morphological changes; microscopy; ontogenesis.

INTRODUCTION

The structure of endocrine disease is characterized by a significant spread of thyroid pathology, namely, about 47% is precisely thyroid pathology, which continues to grow [1, 2].

An important reason for the growth of thyroid pathology is a decrease in the functional activity of the thyroid gland due to the influence of a number of environmental factors [3, 4]. Although the morphofunctional state of the thyroid gland is the resulting consequence of the direct or indirect action of various natural, environmental, climatic, social and other factors, the main factor of damage is the imbalance of biometals, the leading place in which belongs to iodine deficiency [5, 6]. Thyroid hormones, the component of which is iodine, regulate energy homeostasis, and even a slight decrease in their level is a risk factor for cardiovascular diseases [7–9]. Under conditions of iodine deficiency, cardiovascular dysfunction develops asymptomatically [10].

Adequate synthesis of thyroid hormones is a critically important component for maintaining the health of the cardiovascular system, since the synthesis of proteins and enzymes necessary for the functioning of the endocardium depends on a sufficient amount of iodine, which emphasizes the need for dietary corrections in case of its deficiency [11].

The territories of Ukraine are characterized by a mosaic combination of biogeochemical localities with reduced iodine content in environmental objects and areas with anthropogenic and man-made pollution of the environment with heavy metal ions, substances

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with thyroid-disruptive and radioactive properties.All these factors have the ability to affect various links of the hypothalamic-pituitary-thyroid axis, which can disrupt the synthesis, secretion, and transportation of thyroid hormones, distort their local effect on target cells, and cause functional and organic changes in the gland with subsequent disorders of the entire organism [12, 13, 14].

Taking into account the prevalence of iodine deficiency and consumption of stromogens and fragmentary data on their effects on the endocardium and arteries of various types, there was a need for their comprehensive study.

The aim of the study: to follow the morphofunctional changes in the endocardium, the wall of arteries of various types in the dynamics of the development of iodine deficiency and iodine deficiency combined with the consumption of stromogens in postnatal ontogenesis.

MATERIALS AND METHODS

The experiment was performed on 78 white outbred male rats (39 animals each of sexually immature (3–5 months) and sexually mature (6–8 months) age). 11 animals of both age groups made up 1 group (control), 14 animals each entered 2 and 3 experimental groups with simulated iodine deficiency and material intake on 60 and 90 days of the experiment, respectively. The 4th and 5th research groups consisted of animals of both age groups, which were simulated combined iodine deficiency with the consumption of stromogens [15]. All manipulations were carried out in strict compliance with the rules of humane treatment of animals.

The collection of material for light-optical and electron microscopic studies was carried out on the 60th and 90th day of the experiment. Tissues of the endocardium, aorta, external carotid, and renal arteries were studied. A morphometric, biochemical study with statistical data processing was also conducted [16].

RESULTS AND DISCUSSION

Thyroid status of sexually immature animals of group 1: TSH (0.10±0.01) μIU/ml ($p<0.01$), Tz (3.63±0.12) nmol/l ($p<0.01$), T4 (75.44±4.01) nmol/l ($p<0.01$); in sexually mature individuals – (0.08±0.00) μIU/ml ($p<0.01$), (2.79±0.15) nmol/l ($p<0.01$), (55.18±2.72) nmol/l ($p<0.01$), respectively. Cholesterol content under age-standard conditions is: in sexually immature rats (1.60±0.05) mmol/l ($p<0.01$), in sexually mature rats – (1.40±0.09) mmol/l ($p<0.01$). Ioduria in sexually immature animals of group 1 is (97.13±5.40) μg/l, in sexually mature animals – (101.06±3.44) μg/l ($p<0.01$).Thyroid status of sexually immature animals of 2 groups: TSH (0.17±0.02) μIU/ml ($p<0.01$), Tz (3.46±0.36) nmol/l ($p<0.01$), T4 (75.49±9.60) nmol/l ($p<0.01$); in sexually mature – (0.12±0.01) μIU/ml ($p<0.01$), (2.97±0.37) nmol/l ($p<0.01$), (67.49±8.25) nmol/l ($p<0.01$), respectively. Cholesterol content on the 60th day of the experiment is: in sexually immature rats (1.63±0.17) mmol/l ($p<0.01$), in sexually mature rats – (1.39±0.12) mmol/l ($p<0.01$). Ioduria in sexually immature animals of group 2 is (2.73±0.29) μg/l, in sexually mature animals – (3.77±0.34) μg/l ($p<0.01$).

In light microscopic examination on the 60th day of iodine deficiency, the endocardium has the appearance of a thin eosinophilic line lining the myocardium, with well-contoured oval-shaped nuclei in the cytoplasm of endothelial cells, in some loci they are rounded. Endotheliocyte nuclei are not visualized in all fields of view, they have different intensity of basophilia. The cytoplasm of endothelial cells is weakly eosinophilic, with indistinct boundaries.

Submicroscopically, general membrane organelles are found in the cytoplasm of endotheliocytes. The lumenal surface of the plasmolemma of cells forms a relief contour, forming numerous protrusions. The amorphous substance of the subendothelial layer has an average electron density. In the muscle-elastic layer, smooth muscle cells are visualized, in the cytoplasm of which mitochondria and endoplasmic reticulum are clearly identified. However, in some areas, loci of optical illumination are visible (Fig. 1). The content of endothelin-1 in the blood of sexually immature animals increased by 2.9 % ($p<0.05$), it did not change in sexually mature animals.

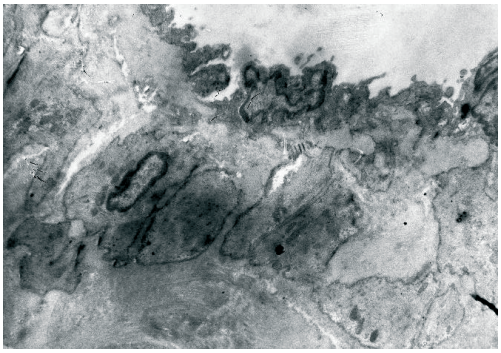

Fig. 1. Structural organization of the endocardium of a sexually mature animal on the 60th day of iodine deficiency. Electronic microphotograph. x4000.

When microscopically studying the wall of the vessels of the arterial bed, it was established that in the arteries of elastic, mixed and muscular types, all layers are identified, however, the perimeter of their lumen is deformed due to the unevenness of the convolutions of the connective tissue framework. The internal elastic membrane forms uneven protrusions along the perimeter of the lumen. The endothelial layer of the intima is illuminated, the nuclei of endotheliocytes, which are mainly located at the apical poles, are not visible in all fields of view. The nuclei of smooth muscle cells of the middle layer are multidirectional, with varying degrees

of basophilia. The adventitia membrane is veiled, has islands of layers.

Submicroscopically, it was established that the endothelial cells lie on the basement membrane, under which the subendothelial layer with varying intensity of electron density is located. A noticeable increase in the size of organelles and multiple protrusions of their lumenal plasmolemma are visualized in the cells. The internal elastic membrane is observed with luminal loci. The sarcoplasm of smooth myocytes is illuminated and has a granular-fibrillar structure. Mitochondria and myofilaments are visualized in it. Membrane organelles are expanded in fibroblasts. Connective tissue fibers are surrounded by an amorphous substance.

According to morphometric analysis, in sexually immature animals, the thickness of the wall of the aorta, external carotid and renal arteries increased by 0.9 % ($p<0.05$), 0.9 % ($p<0.05$) and 0.6 % ($p<0.05$), respectively. In sexually mature animals, this parameter increased by 0.2 % ($p<0.05$), 0.7 % ($p<0.05$) and 1.1 % ($p<0.05$), respectively.

Thyroid status of sexually immature animals of 3 groups: TSH (0.16±0.02) μIU/ml ($p<0.01$), Tz (3.47±0.39) nmol/l ($p<0.01$), T4 (51.31±6.53) nmol/l ($p<0.01$); in sexually mature individuals – (0.23±0.03) μIU/ml ($p<0.01$), (2.43±0.29) nmol/l ($p<0.01$), (54.91±7.05) nmol/l ($p<0.01$), respectively. Cholesterol content on the 90th day of the experiment is: in sexually immature rats (1.66±0.20) mmol/l ($p<0.01$), in sexually mature rats – (1.44±0.16) mmol/l ($p<0.01$). Ioduria in sexually immature animals of group 3 is (1.89±0.24) μg/l, in sexually mature animals – (2.29±0.21) μg/l ($p<0.01$).

On the 90th day of the iodine deficiency experiment, the endocardium is visualized as an unevenly swollen, veil-like line, that covers the myocardium, with an illuminated subendothelial layer (Fig. 2). Endotheliocyte nuclei have varying degrees of basophilia, are located at different cell levels, and are flattened. The cytoplasm of endotheliocytes has a mesh structural organization.

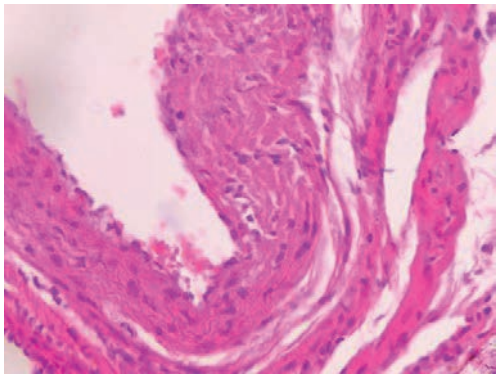

Fig. 2. The structure of the endocardium on the 90th day of iodine deficiency in sexually mature animals. Staining with hematoxylin and eosin. x400.

Under a submicroscopic examination, endothelial cells are characterized by an average electron density with bad differentiated general organelles. A swollen, homogeneous subendothelial layer is revealed in the form of a homogeneous deformed strip. Swollen multidirectional collagen fibers are localized in the muscle-elastic layer surrounded by an illuminated amorphous substance. Noticeable vacuolization of the sarcoplasm of smooth muscle cells and swelling of the fibers of the muscle-elastic layer. The content of endothelin-1 in the blood of sexually immature animals increased by 4.3 % ($p<0.05$), in sexually mature animals it increased by 1.2 % ($p<0.05$).

When studying the walls of arteries of elastic, muscular and mixed types, edematous manifestations are often revealed, flattening of the forms of endotheliocytes is noted, not all cells visualize nuclei (Fig. 3). Adhesion of formed blood elements covering endotheliocytes is observed in the vessel lumen. Endothelial cells are located on a poorly differentiated thin basement membrane. Their lumenal surface has a bad contour around the vessel perimeter. The cytoplasm is diffusely granular with alternating optical illumination.

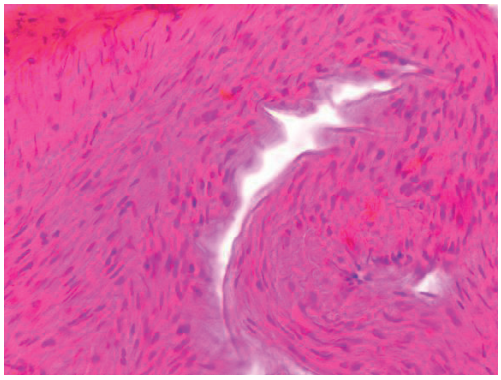

Fig. 3. The structure of the wall of the renal artery on the 90th day of the iodine-deficient state of a sexually mature animal. Staining with hematoxylin and eosin. x400.

Submicroscopically, it is noticeable that the subendothelial layer has a low electron density. The collagen-elastic framework of the middle layer is deformed, swollen, the bundles of elastic fibers are uneven. Elastic and collagen fibers in the middle layer of the arterial wall are swollen and distended. The nuclei of smooth myocytes of the media are multidirectional, stained weakly basophilic. In some fields of vision, the sarcoplasm of cells is illuminated. Adventitia is represented by stratified collagen fibers in the swollen amorphous component of the intercellular substance.

According to morphometric analysis, in sexually immature animals, the thickness of the wall of the aorta, external carotid and renal arteries increased by 1.0 % ($p<0.05$), 1.2 % ($p<0.05$) and 0.8 % ($p<0.05$), respectively. In sexually mature animals, this parameter

increased by 0.6 % (p<0.05), 1.3 % (p<0.05) and 1.7 % (p<0.05), respectively.

Thyroid status of sexually immature animals of 4 groups: TSH (0.18±0.02) μIU/ml (p<0.01), Tz (3.44±0.36) nmol/l (p<0.01), T4 (74.40±7.10) nmol/l (p<0.01); in sexually mature individuals – (0.14±0.01) μIU/ml (p<0.01), (2.39±0.24) nmol/l (p<0.01), (63.60±7.46) nmol/l (p<0.01), respectively. Cholesterol content on the 60th day of the experiment is: in sexually immature rats (1.66±0.19) mmol/l (p<0.01), in sexually mature rats – (1.44±0.15) mmol/l (p<0.01). Ioduria in sexually immature animals of group 2 is (1.42±0.16) μg/l, in sexually mature animals – (1.92±0.21) μg/l (p<0.01).

During light microscopy, the endocardium has the appearance of an uneven line lining the myocardium. Endotheliocyte nuclei are not visualized in all fields of view, they have different intensity of basophilia. Cytoplasm is weakly eosinophilic, with indistinct boundaries.

During ultrastructural examination, membranous organelles of a rounded shape are found in the cytoplasm of endotheliocytes. The lumenal surface forms a relief contour. Subendothelial layer of medium electron density. Locus of optical illumination are visible in the muscle-elastic layer (Fig. 4). The content of endothelin-1 in the blood of sexually immature animals increased by 4.3 % (p<0.05), in sexually mature animals – by 2.4 % (p<0.05).

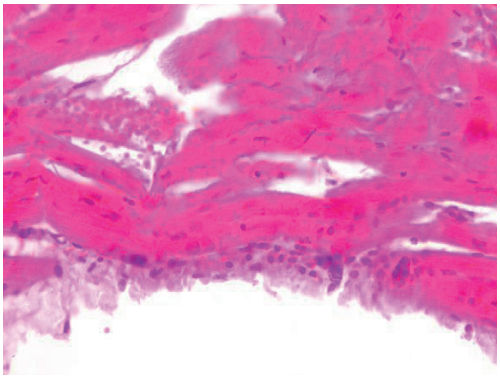

Fig. 4. Endocardium of a sexually mature animal on the 60th day of iodine deficiency with stromogens. Staining with hematoxylin and eosin. x400.

In the wall of arteries of different types, their layers are differentiated. The internal elastic membrane forms uneven protrusions along the perimeter of the lumen. Endotheliocyte nuclei are visualized on their apical poles. The nuclei of smooth muscle cells of the middle layer are basophilic stained. The adventitia has islands of stratification (Fig. 5).

According to the morphometric analysis, in sexually immature animals, the thickness of the wall of the aorta, external carotid and renal arteries increased by 0.9 % (p<0.05), 1.1 % (p<0.05) and 0.8 % (p<0.05), respectively. In sexually mature animals, this parameter increased by 0.3 % (p<0.05), 0.9 % (p<0.05) and 1.4 % (p<0.05), respectively.

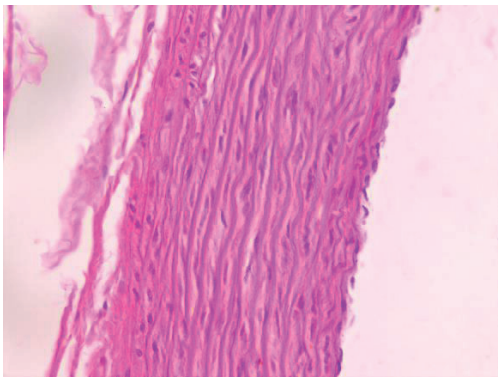

Fig. 5. Aorta of a sexually immature animal on the 60th day of iodine deficiency with stromogens. Staining with hematoxylin and eosin. x400.

Under a submicroscopic examination, endotheliocytes are located on the basement membrane, under which a subendothelial layer with varying intensity of electron density is visible. Mitochondria and myofilaments are visualized in the illuminated sarcoplasm of smooth muscle cells. Membrane organelles are expanded in fibroblasts. Connective tissue fibers are surrounded by an amorphous substance.

Thyroid status of sexually immature animals of 5 groups: TSH (0.14±0.02) μIU/ml (p<0.01), Tz (3.36±0.33) nmol/l (p<0.01), T4 (50.14±5.73) nmol/l (p<0.01); in sexually mature individuals – (0.26±0.02) μIU/ml (p<0.01), (2.06±0.18) nmol/l (p<0.01), (50.88±5.69) nmol/l (p<0.01), respectively. Cholesterol content on the 90th day of the experiment is: in sexually immature rats (1.68±0.15) mmol/l (p<0.01), in sexually mature rats – (1.49±0.14) mmol/l (p<0.01). Ioduria in sexually immature animals of group 3 is (0.92±0.08) μg/l, in sexually mature animals – (1.54±0.14) μg/l (p<0.01).

On the 90th day of the experiment, edematous changes in the endocardium progress. During light microscopic examination, it has the appearance of a veil-like strip covering the myocardium. Flattened, slightly basophilic-stained nuclei of endotheliocytes are visualized in the light pink cytoplasm. The content of endothelin-1 in the blood of sexually immature animals increased by 5.7 % (p<0.05), in sexually mature animals – by 2.4 % (p<0.05).

Submicroscopically, the cytoplasm of endotheliocytes has an average electron density. There are expanded membrane organelles, as well as vacuoles. The subendothelial layer is swollen, homogenized. Noticeable vacuolization of the sarcoplasm of smooth myocytes and swelling of the fibers of the muscle-elastic layer.

Edema changes are also found in the wall of the examined arteries. Endotheliocytes are flattened,

their nuclei are not identified throughout. The collagen-elastic framework of the media is deformed, the bundles of elastic fibers are uneven. Nuclei of smooth myocytes are unidirectional, weakly basophilic. In some fields of vision, the sarcoplasm is illuminated. The adventitia is edematously changed.

According to morphometric analysis, in sexually immature animals, the thickness of the wall of the aorta, external carotid and renal arteries increased by 1.1 % ($p<0.05$), 1.3 % ($p<0.05$) and 1.0 % ($p<0.05$), respectively. In sexually mature animals, this parameter increased by 0.6 % ($p<0.05$), 1.4 % ($p<0.05$) and 1.8 % ($p<0.05$), respectively.

Ultrastructural examination reveals flattened endotheliocytes on a poorly differentiated basement membrane, under which the subendothelial layer is swollen (Fig. 6).

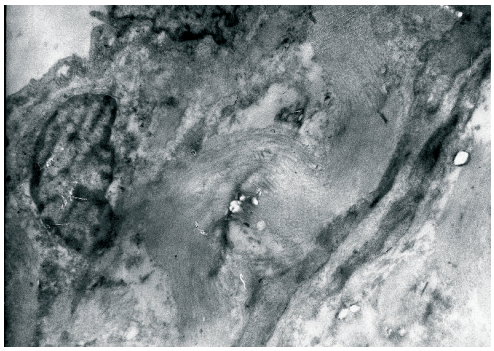

Fig. 6. Ultrastructure of the wall of the carotid artery of a sexually mature animal on the 90th day of iodine deficiency with stromogens. x4800.

The same edematous changes are expressed in the fibers and smooth muscle cells of the arterial wall. Submicroscopically, it is noticeable that the subendothelial layer has a low electron density. The collagen-elastic framework of the middle layer is deformed, swollen, the bundles of elastic fibers are uneven. Elastic and collagen fibers in the middle layer of the arterial wall are swollen and distended. Adventitia is represented by stratified collagen fibers in the swollen amorphous component of the intercellular substance.

Iodine is a key trace element for the synthesis of thyroid hormones, and thyroid hormones directly affect metabolism, vascular tone, myocardial contractility, lipid profile, and overall cardiovascular risk [17, 18, 19]. Iodine deficiency can cause a decrease in the production of thyroxine and triiodothyronine with a compensatory increase in thyroid-stimulating hormone, which creates conditions for the formation of a hypothyroid state or subclinical dysfunction of the thyroid gland [17, 20]. Modern reviews emphasize that even moderate disorders of thyroid status are associated with dyslipidemia, arterial hypertension, endothelial dysfunction, atherosclerotic process and heart failure [18, 19, 21].

Of particular importance is the fact that the relationship between iodine status and the cardiovascular system is not limited to clinically pronounced hypothyroidism. In population studies, the concentration of iodine in urine was considered as a marker of iodine supply and was associated with metabolic disorders, mortality or cardiovascular consequences [22–24]. In particular, U-shaped associations between iodine status and metabolic disturbances suggest that both iodine deficiency and excess may be undesirable for metabolic homeostasis [22]. Iodine status has also been considered as a potential long-term risk factor in US and Spanish adult mortality studies [23, 24].

Mechanistically, the effect of iodine deficiency on the heart can be realized through a decrease in thyroid stimulation of cardiac muscle cells, a change in the expression of genes that regulate myocardial contractility, a violation of lipid metabolism, an increase in systemic vascular resistance, and the development of tissue hypoxia. In hypothyroid conditions, a decrease in cardiac output, diastolic dysfunction, an increase in cholesterol level, and the formation of an unfavorable cardiometabolic profile are described [18, 19, 21]. This is an important basis for the morphological study of the heart, particularly the endocardium, since the endocardium and subendocardial structures are sensitive to changes in hemodynamics, swelling of connective tissue components, microcirculation disorders, and metabolic imbalance.

Another factor that can increase the consequences of iodine deficiency is the intake of current-forming substances with food products. Such products primarily include plants of the Brassicaceae family, soy, millet, cassava and other sources of compounds capable of influencing thyroid metabolism [25–27]. Glucosinolates and their metabolites, in particular thiocyanates and goitrin, can compete with iodide or affect the processes of iodine organization, especially under conditions of insufficient iodine supply [26, 27]. At the same time, a modern systematic review on Brassica vegetables shows that, with adequate iodine intake, the usual dietary use of such products mostly does not have a clinically significant negative effect on the thyroid gland [27].

Experimental data are particularly useful for analyzing the combined effect of iodine deficiency and stromogenic products. In the work of Paśko et al. it was shown that the interaction of iodine and glucosinolates from rutabaga sprouts affects biomarkers of thyroid gland function in male rats [28]. In a subsequent study by the same research group, it was found that animals with models of thyroid damage responded differently to the consumption of Brassica sprouts; under conditions of a hypothyroid state, such products could increase negative changes in certain biochemical indicators [29].

For the endocardium, edematous changes, remodeling of the connective tissue fibers, microcirculation disturbances, and secondary changes related to hemodynamic and metabolic imbalance are potentially important. That is why further morphological, morphometric and ultrastructural study of the endocardium under conditions of isolated iodine deficiency and its combination with stromogenic factors is relevant for experimental cardiomorphology [29, 30].

CONCLUSIONS

Thus, the available data allow us to consider iodine deficiency as a systemic factor that can affect the cardiovascular system due to thyroid dysfunction. The combined intake of current-generating substances can increase this effect, especially if iodine deficiency has already formed.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Вплив йододефіцитного стану та струмогенних продуктів на органи серцево-судинної системи

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Анотація. На сьогодні йододефіцитні захворювання становлять глобальну медико-соціальну проблему: згідно з даними ВООЗ, різноманітні порушення здоров'я, зумовлені дефіцитом йоду, посідають третє місце серед 38-ми найпоширеніших неінфекційних захворювань. Частота ураження органів серцево-судинної системи та поширеність йододефіциту є передумовою вивчення впливу тиреоїдного дисбалансу на серце та кровоносні судини. Метою було простежити за морфофункціональними змінами в ендокарді та стінці артерій різного типу в динаміці розвитку йододефіциту в постнатальному онтогенезі. Роботу виконано на експериментальних тваринах статевонезрілого та статевозрілого віку. Досягнення стану йододефіциту підтверджується показниками йодурії та тиреоїдним профілем. Як на 60, так і на 90 доби йододефіцитного стану в усіх досліджених органах виникають набрякові зміни в сполучнотканинних складових, у стінці кровоносних судин, особливо в ендотеліальному шарі, що підтверджено за допомогою світлооптичного та електронно-мікроскопічного методів дослідження. Таким чином, наявні дані дозволяють розглядати йододефіцит як системний фактор, що через тиреоїдну дисфункцію здатний впливати на серцево-судинну систему. Комбіноване надходження струмогенних речовин може посилювати цей вплив, особливо якщо дефіцит йоду вже сформований.

Ключові слова: експеримент; щури; серце; артерії; метаболічні порушення; морфологічні зміни; мікроскопія; онтогенез.

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Peculiarities of morphogenesis of the urinary system of the laboratory mouse

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Abstract. The process of initiation and formation of the urinary system is similar among mammals. Experimental models using the laboratory mouse serve as an effective tool for elucidating the mechanisms of urinary tract development, since analogous studies on human embryos are associated with serious methodological and bioethical limitations. An important region that ensures the functioning of the upper and lower parts of the urinary system is the ureterovesical junction. In the definitive state, it performs the function of a physiological valve that provides unobstructed unidirectional urine passage. The study of its formation is fundamental for understanding the etiology of anomalies in this region. The aim of the study was to determine the main regularities and chronological sequence of prenatal ontogenesis of the ureterovesical junction in the laboratory mouse. The study was performed on 15 series of histological sections of laboratory mouse embryos. The material was obtained from the collection of the Department of Histology, Cytology and Embryology of Bukovinian State Medical University. A complex of morphological research methods was applied (morphometry, microscopy, three-dimensional computer reconstruction, and statistical analysis). In the early stages of mammalian development, the mesonephric (Wolffian) ducts open into the cloaca, which separates into the caudal part of the hindgut and the urogenital sinus, the primordium of the urinary bladder and urethra. This period covers days 10–15 of gestation (stages E10.5–14.5) in the laboratory mouse, corresponding to weeks 4–8 of gestation in humans. The caudal part of the mesonephric duct is the anlage of the upper urinary tract. In the laboratory mouse, at stage E10.5–11.5, the cranial part of the ureteric bud connects with the renal mesenchyme and forms the renal collecting system, whereas the caudal part of the ureteric bud differentiates into the ureter. During E10.5, the ureters connect with the urinary bladder via the common nephric duct. By stage E14.5, the ureters have separated from the mesonephric ducts and fused with the structures of the urinary bladder, in particular with the anlage of Lieutaud's trigone. Thus, the normal architectonics of the intramural segment and ureteral orifice in the laboratory mouse directly depends on coordinated remodeling of the common nephric duct through local apoptosis at stage E11–E13. Differentiation of the ureter from the mesonephric duct and its connection with the urinary bladder in the laboratory mouse are ensured by a sequence of morphological transformations: apoptosis of the common nephric duct at stage E11–E12, fusion of the epithelial layers of the ureter and urinary bladder at stage E13, and accelerated growth of the urogenital sinus during E12–E14.

Keywords: anatomy; embryology; microanatomy; comparative anatomy; urinary system; sphincter muscles; laboratory mouse; human.

INTRODUCTION

The formation of a functionally complete urinary system is a complex and sequential process of histogenesis, differentiation of primordia, and organogenesis of its components, which determines critical periods already at the early stages of prenatal ontogenesis in mammals. Excretion of toxic metabolic products and maintenance of body homeostasis directly depend on

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coordinated regulation of temporal transformations of primordia and subsequent complication of the histological structure and syntopic changes of relatively independent organs of the upper (kidneys, ureters) and lower (urinary bladder, urethra) urinary tract. An important segment that ensures the connection and functioning of these two divisions is the ureterovesical junction. In the mature organism, it functions as a physiological contractile complex that ensures and controls unobstructed urine passage, preventing reflux during contraction of the detrusor muscle of the bladder [1]. Pathological disorders of morphogenesis of the ureterovesical junction cause urinary system anomalies that are included in CAKUT syndrome (Congenital Anomalies of the Kidney and Urinary Tract), which occurs in 1–2 % of newborns. This group of combined congenital malformations of the kidneys and urinary tract includes, in particular, such anomalies as vesicoureteral reflux, megaureter, ectopia of the ureteral orifice, ureteral duplication, and ureterocele [2–5].

The sources of the primordia and the process of urinary system formation are similar in mammals [6–8]. The use of the laboratory mouse as an experimental model serves as an effective tool for detailed study of urinary tract morphogenesis, since analogous studies on human embryos are associated with certain methodological and bioethical limitations [9–11].

The upper and lower urinary tracts have different embryological origins. Fusion of the ureteric bud, which branches from the caudal part of the mesonephric (Wolffian) duct, with the urogenital sinus occurs through cellular remodeling and spatial transformations of this region. For a long time, the theory of Mackie and Stephens (1975) [12] remained the generally accepted paradigm of embryogenesis of the lower urinary tract; it stated that formation of the ureterovesical junction and Lieutaud's trigone occurs through morphological expansion of the ureteric bud and its subsequent integration into the wall of the urogenital sinus. Modern studies on laboratory mouse embryos using cell-lineage labeling have led to a revision of this theory. It was established that the ureteric bud at the site of fusion with the mesonephric duct does not differentiate into urinary bladder structures but regresses under the influence of regulated apoptosis, which is a prerequisite for successful separation of the ureter from the mesonephric duct and normal morphogenesis of the sphincter complex. Despite the morphogenetic similarity of urinary system formation among mammals and substantial progress in morphological, immunohistochemical, and molecular-genetic studies, obtaining new data in comparative embryology of humans and animals remains relevant [13–16].

The aim of the study: to determine the main regularities and chronological sequence of prenatal ontogenesis of the ureterovesical junction in the laboratory mouse.

MATERIAL AND METHODS

The study was performed on 15 series of histological sections of laboratory mouse embryos. The material was obtained from the collection of the Department of Histology, Cytology and Embryology of Bukovinian State Medical University. A complex of morphological research methods was applied (morphometry, microscopy, three-dimensional computer reconstruction, and statistical analysis).

The Biomedical Ethics Commission of Bukovinian State Medical University (Protocol No. 5 dated 19.02.2026) found no violations of moral and legal norms in the conduct of the scientific study.

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RESULTS AND DISCUSSION

In the early stages of mammalian development, the mesonephric (Wolffian) ducts open into the cloaca, which separates into the caudal part of the hindgut and the urogenital sinus, the primordium of the urinary bladder and urethra. This period covers days 10–15 of gestation (stages E10.5–14.5) in the laboratory mouse, corresponding to weeks 4–8 of gestation in humans (Fig. 1). The caudal part of the mesonephric duct is the anlage of the upper urinary tract. In the laboratory

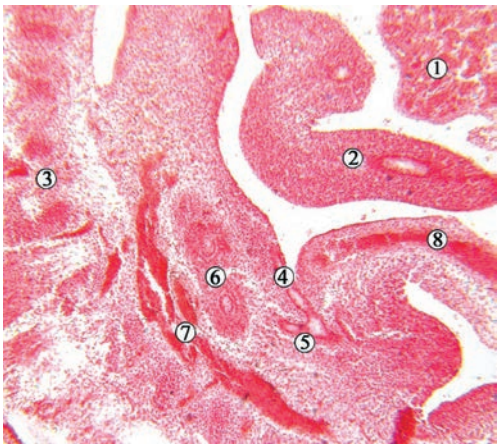

Fig. 1. Parasagittal section of a laboratory mouse embryo at stage E11. Hematoxylin and eosin staining. Photomicrograph. Magnification x70: *1 – liver; 2 – midgut; 3 – vertebral column primordia; 4 – mesonephric duct; 5 – ureteric bud; 6 – metanephric primordium; 7 – dorsal aorta; 8 – allantois.*

mouse, at stage E10.5–11.5, the cranial part of the ureteric bud connects with the renal mesenchyme and forms the renal collecting system, whereas the caudal part of the ureteric bud differentiates into the ureter. During E10.5, the ureters connect with the urinary bladder via the common nephric duct. By stage E14.5, the ureters separate from the mesonephric ducts and fuse with the structures of the urinary bladder, in particular with the anlage of Lieutaud's trigone (Fig. 2).

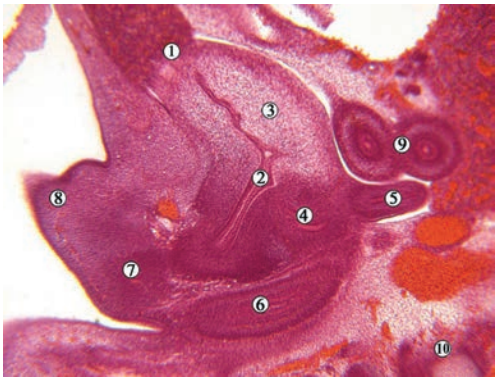

Fig. 2. Parasagittal section of a laboratory mouse embryo at stage E14.5. Hematoxylin and eosin staining. Photomicrograph. Magnification x70: *1 – allantois; 2 – anlage of Lieutaud's trigone; 3 – urinary bladder; 4 – intramural segment of the ureters; 5 – common nephric duct; 6 – hindgut; 7 – cloaca; 8 – genital tubercle; 9 – midgut; 10 – primordium of the vertebral column.*

The architectonics of the position of the intramural segment and the ureteral orifice in Lieutaud's trigone depends on normal morphogenesis of the common nephric duct, ureter, and mesonephric duct.

Expansion of the common nephric duct is the first step in remodeling of the distal part of the ureter. This process occurs during E11–E13 with the formation of a multilayered epithelium lining it. Its histological pattern differs from the epithelial plate of the mucosa of the ureters and mesonephric ducts. At stage E14, cells of the common nephric duct undergo regression or may differentiate into the structures of Lieutaud's trigone.

Discussion. Studies emphasize that the common nephric duct probably regresses during ureteral maturation by stage E13 rather than differentiating into Lieutaud's trigone [12, 17]. This is confirmed by data on signs of apoptosis of the common nephric duct at E11, whereas signs of regression were absent in the caudal part of the Wolffian duct and in the ureter [12, 18]. Programmed cell death was observed in the ureteral lumen at later stages, before the formation of a functional junction with the urinary bladder. At E15, apoptotic cells were detected in the caudal part of the ureter, which was blocked up to this stage by Chwalla's membrane. This is a temporary two-layered epithelial septum that, in the early stages of mammalian embryogenesis, separates the internal lumen of the common nephric duct from the cavity of the urogenital sinus. Theoretically, apoptosis in the caudal segment of the ureter may be important for the formation of its lumen. The process of local apoptosis in the ureteral lumen at stage E14–E15 may represent degeneration of Chwalla's membrane [12, 19].

Expansion of the common nephric duct and its subsequent apoptosis are important processes for separating the ureter from the Wolffian duct; however, it has not been definitively clarified how, after separation, the ureter assumes its definitive position in the urinary bladder. Analysis of studies suggests two hypotheses. According to the first, the intramural segment of the ureter reaches its definitive position by migrating along the urogenital sinus. According to the second, the ureter is displaced as it is encompassed by the enlarging urogenital sinus. In both hypotheses, a cascade of morphological events is observed: apoptosis between E11 and E12, which permits separation of the ureter from the Wolffian duct; fusion of the ureteral epithelium with the bladder epithelium, which occurs at E13; and accelerated growth of the urinary bladder, which is observed between E12 and E14.

In addition to the stages of normal embryonic development of the urinary system, regularities in the development of pathological morphogenesis have been identified. The Weigert – Meyer law is one of the fundamental rules in embryology and urology that describes the anatomical position of the ureters in cases of complete duplication of the renal pelvis and ureters [2, 12]. Thus, if two separate ureters are formed, they do not open into the urinary bladder randomly but according to a clear rule: the ureter from the upper pole of the kidney passes lower and enters the urinary bladder more caudally and medially than normal. The ureter from the lower pole of the kidney enters the urinary bladder more cranially and laterally relative to the upper ureter. Its position is closer to normal, but its anatomical course is shorter. This anatomical paradox is accompanied by a prevailing pathology for each ureter. The ureter from the upper pole often has pathology of the intramural segment with development of ureterocele or obstruction with hydronephrosis of part of the kidney. The ureter from the lower pole enters the urinary bladder more cranially and at a more direct angle, resulting in vesicoureteral reflux [5]. We also observed this feature in studies of human fetuses (Figs. 3, 4).

The theoretical model of development of this anomaly assumes that when two branches of the ureteric bud form on the Wolffian duct, the ureter that appears first and corresponds to the lower end of the organ occupies its position more rapidly. The second ureteric anlage from the upper pole shifts together with the Wolffian duct caudally and more medially,

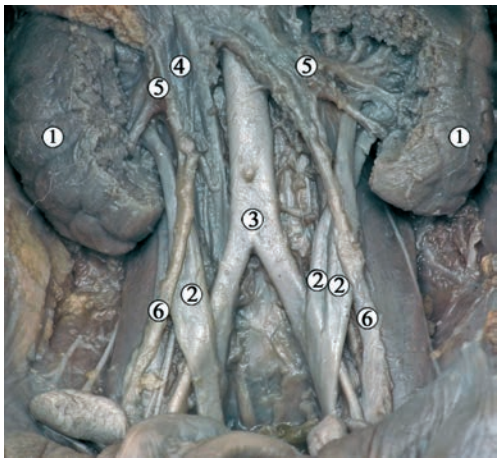

Fig. 3. Retroperitoneal organs of a 6-month-old male human fetus. Photograph of a macrospecimen. Magnification x3: *1 – kidneys; 2 – ureters; 3 – aorta; 4 – inferior vena cava; 5 – renal veins; 6 – testicular veins.*

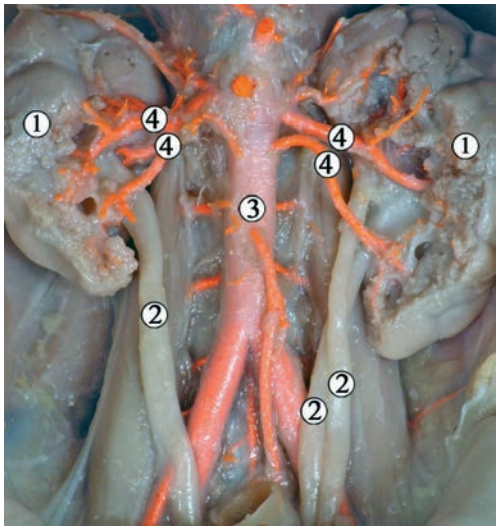

Fig. 4. Retroperitoneal organs of a 6-month-old female human fetus. The arteries are filled with a lead-based mixture. Photograph of a macrospecimen. Magnification x3.0: *1 – kidneys; 2 – ureters; 3 – aorta; 4 – renal arteries; 5 – accessory renal arteries.*

causing the ureters to change places. Studies indicate that apoptosis of the common nephric duct depends on signals from bladder tissues and occurs only in close proximity to these signals. To confirm this, a model of formation of an accessory ureteric bud in the laboratory mouse was reproduced, induced by exposure to high levels of retinoic acid during ureteric bud formation. These studies show that formation of the ureteric bud in a position close to the urogenital sinus may be crucial for receiving signals that induce programmed cell death in structures of the common nephric duct, whereas tissues of the common nephric duct associated with ureteric bud branches that form at higher positions on the Wolffian duct may persist because they are outside the range of signals arising from the urinary bladder, which normally induce apoptosis [12].

Summarizing these data, it should be noted that formation of the ureterovesical junction has features of both normal and abnormal development. Its proper anatomical architectonics ensures unobstructed urine passage and plays a decisive role in maintaining urodynamics, forming a reliable sphincter complex in the mature organism. Disruption of normal embryogenesis of this region causes the development of anomalies included in the structure of CAKUT syndrome. Therefore, further study of the molecular-genetic mechanisms of formation of this segment is one of the most relevant tasks of modern experimental embryology.

CONCLUSIONS

1. The normal architectonics of the intramural segment and ureteral orifice in the laboratory mouse directly depends on coordinated remodeling of the common nephric duct through local apoptosis at stage E11–E13.

2. Differentiation of the ureter from the mesonephric duct and its connection with the urinary bladder in the laboratory mouse are ensured by a sequence of morphological transformations: apoptosis of the common nephric duct at stage E11–E12, fusion of the epithelial layers of the ureter and urinary bladder at stage E13, and accelerated growth of the urogenital sinus during E12–E14.

3. Disturbance of urinary system development, according to the Weigert – Meyer law, is caused by disorders of apoptosis of the common nephric duct and leads to ureterocele, obstruction, and vesicoureteral reflux.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Особливості морфогенезу сечової системи миші лабораторної

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Анотація. Процес закладки та формування сечової системи є подібним серед ссавців. Експериментальні моделі з використанням миші лабораторної слугують ефективним інструментом для розкриття механізмів розвитку сечовидільного тракту, оскільки аналогічні дослідження на ембріонах людини супроводжуються серйозними методичними та біоетичними обмеженнями. Важливою ділянкою, що забезпечує функціонування верхнього та нижнього відділів сечової системи, є сечовідно-міхурове сполучення. У дефінітивному стані воно виконує функцію фізіологічного клапана, що забезпечує безперешкодний односпрямований пасаж сечі. Вивчення його формування є фундаментальним для розуміння етіології аномалій цієї ділянки. Метою роботи було з'ясувати основні закономірності та хронологічну послідовність пренатального онтогенезу сечовідно-міхурового сполучення миші лабораторної. Дослідження проведено на 15 серіях гістологічних зрізів препаратів зародків миші лабораторної. Матеріал використано із колекції кафедри гістології, цитології та ембріології Буковинського державного медичного університету. Застосовано комплекс методів морфологічного дослідження (морфометрія, мікроскопія, тривимірне комп'ютерне реконструювання, статистичний аналіз). На ранніх стадіях розвитку ссавців мезонефричні (Вольфові) протоки відкриваються в клоаку, яка розділяється на каудальний відділ задньої кишки та сечостатеву пазуху, зачаток сечового міхура та сечівника. Цей період охоплює 10–15 дні гестації (стадії E10.5–14.5) миші лабораторної, що відповідає 4–8 тижням гестації у людини. Зачатком верхніх сечових шляхів є каудальна частини мезонефричної протоки. У миші лабораторної на стадії E10.5–11.5 краніальна частина сечовідного зачатка з'єднується з мезенхімою нирки та утворює порожнинну систему нирки, тоді як каудальна частина сечовідного зачатка диференціюється у сечовід. Під час E10.5 сечоводи з'єднуються з сечовим міхуром через загальну нефральну протоку. Вже на стадії E14.5 сечоводи відокремлюються від мезонефричних проток і зливаються зі структурами сечового міхура, зокрема із закладкою трикутника Льєто. Отже, нормальна архітектоніка інтрамурального відділу та вічка сечовода миші лабораторної безпосередньо залежить від координованого ремоделювання загальної нефральної протоки шляхом локального апоптозу на стадії E11–E13. Диференціація сечовода від мезонефричної протоки та його з'єднання з сечовим міхуром у миші лабораторної забезпечуються послідовністю морфологічних перетворень: апоптозом загальної нефральної протоки на стадії E11–E12, злиттям епітеліальних шарів сечовода та сечового міхура під на стадії E13, а також пришвидшенням росту сечостатевої пазухи у терміни E12–E14.

Ключові слова: анатомія; ембріологія; мікроанатомія; порівняльна анатомія; сечова система; м'язи-замикачі; миша лабораторна; людина.

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Circadian rhythms and neuroprotective effects of melatonin in the central nervous system

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Abstract. This article summarizes current data on the role of melatonin in regulating circadian rhythms and maintaining the functional activity of the central nervous system. It examines the main mechanisms of neuroendocrine control of melatonin secretion, as well as the role of the suprachiasmatic nucleus of the hypothalamus and the pineal gland in maintaining the body's circadian rhythm. Current concepts regarding the receptor mechanisms of melatonin action and the functional characteristics of MT1 and MT2 receptors in brain structures are discussed. In addition to its chronobiological effects, melatonin participates in cellular defense mechanisms. The role of melatonin as an endogenous antioxidant and modulator of cellular signaling processes has been analyzed. Particular attention is paid to its role in regulating mitochondrial function, supporting oxidative phosphorylation, controlling oxidative stress, and maintaining cellular homeostasis. Data are presented on the participation of melatonin in the functioning of the brain's glymphatic system, the elimination of neurotoxic metabolites, and the maintenance of metabolic balance in nervous tissue. An analysis of the results of studies was carried out, which confirm the neuroprotective and anti-inflammatory effects of melatonin in lesions of the central nervous system. Accumulated experimental and clinical data confirm the promise of further study of melatonin as a biologically active molecule with a wide spectrum of effects on the body.

Keywords: circadian rhythms; central nervous system; melatonin; neuroprotection; mitochondria; antioxidant activity.

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INTRODUCTION

Circadian rhythms are a fundamental mechanism of temporal organization of physiological processes, which ensures the adaptation of the organism to cyclic changes in the environment and maintenance of internal homeostasis. The regulation of daily biorhythms is carried out by a complex neuroendocrine system, the central link of which is the suprachiasmatic nucleus (SCN) of the hypothalamus, which functions as the main circadian pacemaker of the organism [1].

The pineal gland plays a central role in ensuring the daily organization of physiological processes, the functional activity of which is associated with the "light-dark" cycle and neurohumoral regulation of biological rhythms.

One of the primary functions of the pineal gland is the transformation of information about changes in the light regime of the environment into neuroendocrine signals that shape the body's adaptation to daily fluctuations. Through the synthesis and secretion of melatonin (MT), the pineal gland participates in maintaining circadian rhythmicity and functional balance.

Since MT regulates biological rhythms, it influences sleep and wakefulness, thermoregulation, hormone secretion, metabolic processes, and the body's adaptive responses. Thus, the pineal gland serves as an important chronobiological center that coordinates the synchronization of internal physiological processes with external environmental conditions [1, 2].

MT not only functions as a circadian rhythm regulator and antioxidant, but also acts as an important modulator of gene expression. It regulates the activity of a large number of genes in the central nervous system (CNS), particularly in the SCN [3].

In addition, it modulates genetic activity in various peripheral tissues, which indicates its systemic effect on the functioning of the body and the coordination of biorhythms at the molecular level. Such properties of this hormone emphasize its importance in maintaining physiological balance and adaptation to changes in the external environment. The interaction of epigenetic mechanisms with "clock" genes (Per1, Per2, Cry1, Cry2, Bmal1) provides photoperiodic regulation of circadian and seasonal changes in the physiological functions of the body. Jenwitheesuk et al. [4] in their article indicate that the diversity of melatonin receptor isoforms determines the selectivity of its interaction with natural ligands, and also determines differences in the regulation of the expression of these receptors both in different tissues and at different stages of ontogenesis.

The wide range of biological effects of the neurohormone is largely due to its physicochemical properties and ability to penetrate biological membranes, in particular through the selective blood-brain barrier, reaching the structures of the CNS. In the scientific literature, melatonin is considered one of the most effective endogenous antioxidants in the CNS. Its antioxidant action is realized both by direct neutralization of free radicals (in particular, reactive forms of oxygen and nitrogen), and indirectly by activation of antioxidant enzymes (superoxide dismutase, catalase, glutathione peroxidase) and suppression of pro-oxidant processes. In addition, this molecule helps to stabilize cell membranes, protect mitochondria and reduce the level of oxidative stress, which is important for the optimal functioning of neurons and neuroprotection [5].

According to modern scientific data, considerable attention is paid to the participation of MT in the functioning of the glymphatic system of the brain, which ensures the elimination of neurotoxic compounds and maintenance of neurometabolic balance [6, 7].

The results of experimental and clinical studies identify MT as a highly effective endogenous scavenger of free radicals, which exhibits pronounced cytoprotective properties. In particular, its potential role in the prevention and modulation of the course of neurodegenerative diseases, epilepsy, as well as certain forms of malignant neoplasms has been demonstrated. Such an effect is due to both direct antioxidant activity and the ability to influence key cellular signaling pathways. Scientific works in vitro and in vivo deepen and expand the ideas formed during the last decades, confirming the central role of melatonin in the system of antioxidant protection and anti-inflammatory processes [5, 8, 9].

Scientists [10, 11] are particularly interested in the neurohormone's ability to influence the functional state of mitochondria, stabilize oxidative phosphorylation processes, and reduce the manifestations of oxidative stress.

Due to its anti-inflammatory properties, MT is able to reduce the levels of pro-inflammatory cytokines and suppress the reactive activation of astrocytes and microglia [12, 13].

Separate studies indicate the involvement of the SIRT1 signaling pathway in the implementation of the neuroprotective effects of melatonin [14, 15].

The aim of the study: to summarize the current literature data on the role of melatonin in the regulation of circadian rhythms, the functioning of mitochondria and the provision of neuroprotective mechanisms in the central nervous system.

MATERIALS AND METHODS

This study was conducted as a descriptive literature review incorporating elements of a systematic analysis of current scientific sources. The search for scientific articles was conducted in the international scientometric databases PubMed and Web of Science. The analysis included publications from the past 10 years. The inclusion criteria were full-text articles, systematic reviews, meta-analyses, and experimental and clinical studies focused on the investigation the

role of melatonin in the regulation of circadian rhythms, central nervous system function, mitochondrial activity, and neuroprotective mechanisms. No statistical data analysis was performed within the scope of this study, as the work is of a review nature.

RESULTS AND DISCUSSION

The circadian system and neuroendocrine regulation of melatonin secretion

The suprachiasmatic nucleus of the hypothalamus plays a key role in the regulation of circadian rhythms and the neuroendocrine control of melatonin secretion. It has been established that photoperiodic information reaches the pineal gland after being processed by the SCN of the hypothalamus. Through a feedback mechanism, melatonin modulates rhythmic activity and metabolic processes in this region [16, 17].

The light information detected by the photoreceptors of the retina is transmitted along the fibers of the optic nerve to the SCN of the hypothalamus. Ganglion cells, which express melanopsin and directly perceive light stimuli, play an important role in this process. From the CNS, nerve impulses are transmitted by descending pathways through the hypothalamus and brainstem to the cervical spinal cord.

Then the signals pass through sympathetic fibers through the upper cervical sympathetic ganglion and again go to the skull cavity, reaching the pineal gland. Thus, in scientific research [18, 19] show that such a neuronal network ensures synchronization of the functional activity of the pineal gland with changes in the "light-dark" cycle.

In the central nervous system, SCN neurons directly or indirectly project to various brain regions, such as the hypothalamus, limbic system, choroid plexus, pituitary, median eminence, pineal gland, area postrema, vascular organ of lamina terminalis, periaqueductal gray, ventral tegmental area, and hippocampus (Fig.) [3].

It has been established that in the dark, the activity of most neurons in the SCN decreases, accompanied by the release of norepinephrine, which mediates the activation of pinealocytes and enhances the synthesis of enzymes necessary for the production of the pineal

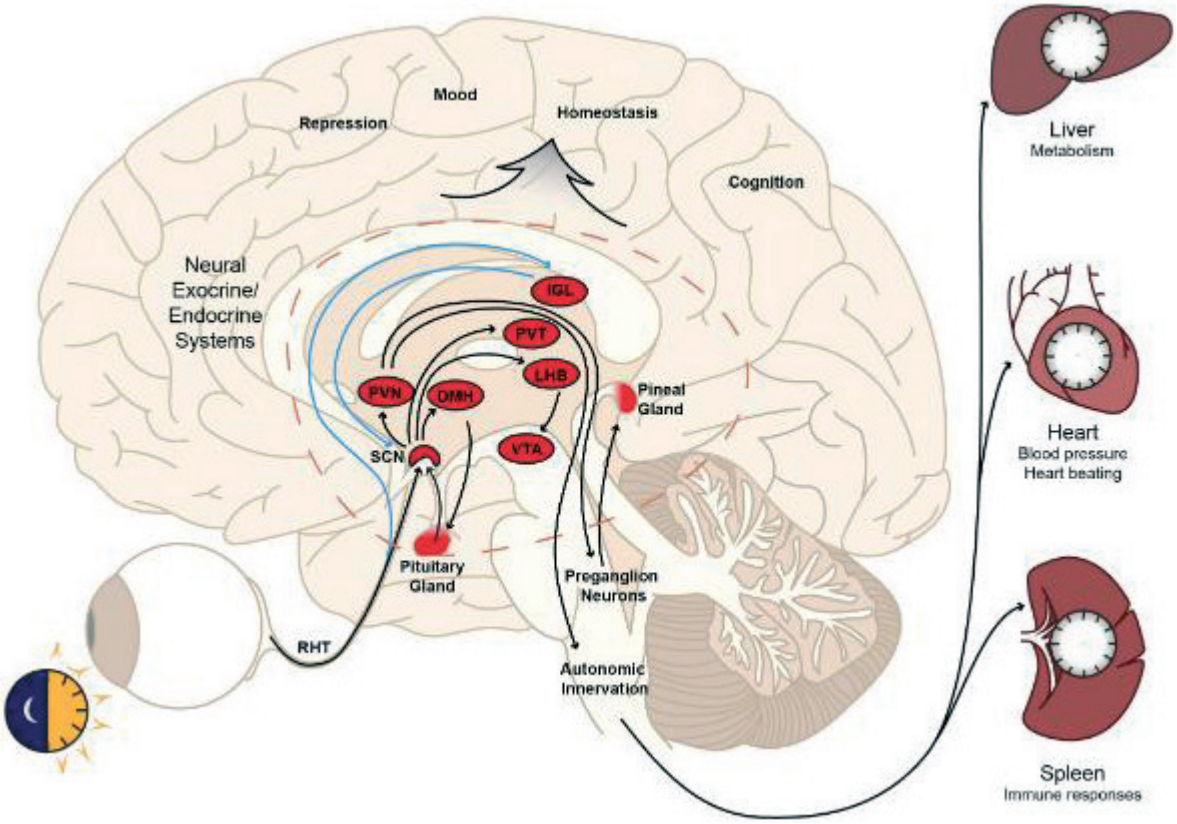

Fig. Circadian clock networks in the brain. *The SCN receives photic information via the RHT and conveys it to other parts of the brain and body (solid black lines). The IGL also receives photic information via the RHT and combines this with nonphotic information. Then, the IGL transmits combined information to the SCN via the GHT (solid blue lines). The majority of photic information is transferred to the SCN via the RHT. The IGL-GHT pathway contributes only a minor part to the photic entrainment process. RHT, the retinohypothalamictract; GHT, the geniculohypothalamic tract; IGL, the intergeniculate leaflet; PVN, the paraventricular nucleus; DMH, the dorsomedial hypothalamus; PVT, the paraventricular thalamic nuclei; LHB; the lateral habenula; VTA, the ventral tegmental area.* ***Source:*** *[3].*

hormone. Bright light rapidly suppresses its secretion, whereas in the absence of light, the circadian rhythm of production is maintained due to the endogenous rhythmic activity of the SCN. The data obtained confirm the existence of an internal circadian mechanism capable of maintaining the temporal coordination of physiological processes even in the absence of external light signals [1, 19].

According to the literature, the daily production of MT by the pineal gland is on average 0.1–0.9 mg [20].

Melatonin secretion is clearly synchronized with the day-night cycle: the highest concentrations are observed during the night period, with maximum levels mainly between midnight and 4 a.m., while during the day its amount is significantly reduced to baseline levels. Such a circadian profile of secretion ensures synchronization of biological rhythms of the body and adaptation of physiological processes to changes in environmental lighting [21, 22].

Rhythmic fluctuations in the neurohormone level are directly related to the peculiarities of its biosynthesis.

The precursor of melatonin is the amino acid tryptophan, which comes from blood plasma. The biosynthesis of indolamine begins with the conversion of tryptophan to 5-hydroxytryptophan, and then to serotonin. The next step is acetylation of serotonin with the participation of the enzyme arylalkylamine-N-acetyltransferase (AA-NAT) with the formation of N-acetylserotonin. This reaction is the key regulatory stage of indoleamine biosynthesis, which determines the speed and intensity of its formation. The final stage includes methylation of N-acetylserotonin by hydroxyindole-O-methyltransferase with the formation of melatonin [23].

The metabolism of the pineal hormone is primarily mediated by cytochrome P450 enzymes in the liver. During biotransformation, it undergoes 6-hydroxylation to form 6-hydroxymelatonin, which is subsequently sulfated and excreted in the urine as 6-sulfatoxymelatonin [24].

It has been established that indoleamine synthesis occurs not only in the pineal gland but also in other tissues and cells of the body, including the retina, bone marrow, immune system cells, organs of the gastrointestinal tract, skin, and placenta [25].

Melatonin receptors and signaling mechanisms

The selective action of MT is mediated by various types of receptors located in many tissues – both on cell membranes and in the cell nucleus. This causes a wide range of physiological effects of the hormone [5, 16, 17].

A significant portion of melatonin's physiological effects is mediated by the MT1 and MT2 membrane receptors, which are encoded by the MTNR1A and MTNR1B genes, located in the 4q35 and 11q21-22 regions, respectively, and belong to the superfamily of G protein-coupled receptors (G protein-coupled receptors, GPCR) [26].

In the central nervous system, MT1 receptors are primarily localized in structures involved in the regulation of circadian rhythms, emotional and neuroendocrine processes, particularly in the hypothalamus, hippocampus, cerebellum, substantia nigra, and ventral tegmental area. Their expression in these structures is associated with melatonin's role in regulating the sleep-wake cycle, cognitive functions, neuroplasticity, and neuroprotection.

MT1 receptors are widely distributed throughout the peripheral nervous system, including the cardiovascular system – such as the heart, aorta, and peripheral blood vessels – where they play a role in regulating vascular tone and blood pressure. In addition, MT1 receptors are found in organs of the immune system – the spleen and lymph nodes – as well as in the reproductive organs. They are also identified in the liver, kidneys, adrenal cortex, pancreas, placenta, mammary gland, and skin, indicating the multifunctional role of melatonin in coordinating metabolic, endocrine, immune, and reproductive processes. Recent studies also indicate that MT1 receptors are involved in antioxidant defense mechanisms, the regulation of mitochondrial function, inflammatory responses, and the maintenance of cellular homeostasis [27, 28].

Unlike MT1 receptors, the distribution of MT2 receptors is less pronounced; however, they are expressed in many tissues and organs. MT2 receptors are found in structures of the central nervous system, including the hypothalamic SHS, the cerebral cortex, the retina, and the pituitary gland. In addition, they are expressed in cells of the immune and reproductive systems, blood vessels, kidneys, the gastrointestinal tract, adipose tissue, and the skin. In addition to their chronobiological function, their activation is associated with the modulation of cellular metabolism, inflammatory processes, and neuroprotective mechanisms [27, 28].

In addition to the highly related membrane receptors MT1 and MT2, low-affinity cytosolic melatonin binding sites (MT3) have been described, which have been identified as the enzyme quinone reductase 2 (QR2). It participates in cellular detoxification processes and the maintenance of redox homeostasis. The interaction of melatonin with MT3/QR2 is associated with the exercise of its antioxidant activity, the regulation of apoptosis, and increased sensitivity of tumor cells to chemotherapeutic agents, which allows this system to be considered a promising therapeutic target in oncology [29, 30].

Lépinay et al. [31] experimentally demonstrated that, following the binding of MT to specific membrane receptors, intracellular signaling cascades are activated, particularly the phospholipase C system. Activation of this pathway is accompanied by the hydrolysis of

phosphatidylinositol-4,5-bisphosphate (PIP2) to form secondary messengers – inositol-1,4,5-trisphosphate (IP3) and diacylglycerol (DAG). A subsequent increase in intracellular calcium concentration and activation of protein kinase C regulate gene expression, cellular secretory activity, and neuroendocrine signaling.

Mitochondrial function and melatonin

Scientific evidence suggests a key role for mitochondria in regulating various aspects of melatonin function, including its biosynthesis, metabolism, and receptor-mediated effects. Unlike the classical concept, according to which hormone production is controlled by circadian rhythms (light/dark cycle) and the pineal gland, modern concepts point to the ability of these organelles to autonomously control its synthesis according to intracellular needs.

MT is localized in mitochondrial membranes and is able to penetrate into their inner space with the help of oligopeptide transporters PEPT1 and PEPT2 located on the membrane. Mitochondria are the central organelles of cellular metabolism, since it is in them that the main synthesis of ATP and the formation of reactive oxygen species (ROS) takes place. At the same time, they are able to accumulate MT, which comes from the bloodstream endogenously or exogenously, and synthesize it independently [32].

Melatonin circulating in the blood can be actively taken up by mitochondria with subsequent accumulation against the concentration gradient [33].

Scientific research [34, 35] have shown that these intracellular energy structures can induce local melatonin synthesis in response to elevated levels of oxidative stress, enabling the cell to adapt rapidly to metabolic changes. It has been established that the concentration of melatonin in mitochondria significantly exceeds its level in the systemic circulation, which is likely due to the need to effectively neutralize ROS, which are intensively generated during the functioning of the electron transport chain. Thus, it has been hypothesized that the primary role of melatonin in mitochondria is to protect the organelle from oxidative stress. In addition, mitochondria-associated melatonin not only acts as an antioxidant but also helps stabilize the membrane potential, optimize oxidative phosphorylation processes, and prevent the opening of the mitochondrial pores. This, in turn, limits the activation of apoptotic cascades and helps maintain cellular viability. Thus, mitochondria are considered not only as a target for melatonin's action but also as an important local center for its synthesis, which is of fundamental importance for maintaining cellular homeostasis.

The study by Gloria Somali-Barranco et al. [36] developed the first photoactivated melatonin ligand with mitochondrial targeting. The authors took into account the high lipophilicity and permeability of the hormone, which ensure its ability to interact with both plasma membrane receptors and receptors located in mitochondria. The obtained results confirmed the functional activity of mitochondrial MT1 receptors and their participation in the regulation of oxidative phosphorylation processes.

In studies conducted by D.X. Tan et al. [35], melatonin was found to stimulate mitophagy – a mechanism for the selective elimination of damaged and dysfunctional mitochondria [37].

As noted by the authors A. De Gaetano et al. [38], this is considered one of the key functions of MT, since an imbalance between mitophagy and the formation of reactive oxygen species is associated with accelerated aging and the progression of neurodegenerative changes.

Neuroprotective effects of melatonin in the central nervous system

Scientific experiments have shown that MT is synthesized and functions in neurons and glial cells as well, confirming its role in the local regulation of CNS functions. The presence of the hormone in brain structures enables the implementation of intracrine, paracrine, and autocrine mechanisms, through which it participates in maintaining CNS homeostasis, controlling neurogenesis, and modulating neurotransmitter release [31, 39].

Melatonin is also characterized by pronounced neuroprotective and antitoxic properties. They are associated with a decrease in the activity of glutamate, suppression of excessive excitability of neurons and increased activity of the GABA-ergic system. Thanks to this, the hormone helps to stabilize the neurotransmitter balance, protect neurons from oxidative stress, and ensure the functional integrity of nervous tissue [40].

Due to its anti-inflammatory properties, MT is capable of reducing levels of the pro-inflammatory cytokines IL-6, TNF-α, and IL-1ß in experimental models of ischemic-reperfusion brain injury, subarachnoid hemorrhage, traumatic brain injury, and hypoxia. It has been established that one of the mechanisms of its neuroprotective action is the inhibition of reactive activation of astrocytes and microglia, accompanied by a reduction in neuroinflammatory reactions in the CNS [13, 41, 42].

It has been demonstrated that the administration of this hormone in cases of traumatic brain injury reduces astrocyte reactivity and inhibits neuronal apoptosis in the hippocampus and dentate gyrus [43, 44].

C. Zhang et al. [45] summarized the results of recent studies indicating that melatonin reduces the extent of ischemic brain damage and the severity of cerebral edema following pathological changes, as well as improves neurological status. These effects are achieved by modulating oxidative stress, neuroinflammatory reactions, apoptosis and autophagy processes,

inhibiting glutamate-mediated excitotoxicity, and correcting mitochondrial dysfunction.

In addition, in neurodegenerative diseases and traumatic brain injuries, melatonin exhibits significant neuroprotective properties by reducing microglial activation and the intensity of the neuroinflammatory response. It has been established that this molecule is capable of inhibiting the transmission of pro-inflammatory signaling pathways, reducing the production of inflammatory mediators, and limiting the development of secondary damage to nervous tissue. These effects preserve the functional state of neurons, reduce oxidative stress, and stabilize cellular homeostasis in the CNS [46, 47].

The brain is one of the organs with the highest metabolic rate, which is accompanied by the intensive production of metabolic byproducts. Consequently, maintaining neuronal homeostasis is an extremely complex yet critically important process, in which the glymphatic system plays a key role [7].

An important component of melatonin's cytoprotective effect is its role in the functioning of this system, whose activity is linked to the circadian regulation of physiological processes.

The delivery of the hormone directly to the cerebrospinal fluid ensures its high concentrations in the ventricular system and subsequent penetration into the nervous tissue through the subarachnoid space and Virchow-Robin spaces [6]. In brain tissue, it realizes pronounced antioxidant, anti-inflammatory and neuroprotective effects due to the elimination of metabolic products and neurotoxic compounds, in particular beta-amyloid and tau protein [48].

Studies conducted using experimental models [14, 15] have shown that indoleamine protects nerve cells not only through its antioxidant activity but also by regulating intracellular signaling mechanisms. It has been established that SIRT1 (silent information regulator 1), which belongs to the family of NAD□-dependent deacetylases, may act as one of the downstream molecular targets of melatonin. Activation of SIRT1 is associated with a reduction in neuroinflammation, suppression of oxidative stress, maintenance of mitochondrial function, and protection of neurons from damage. It has been shown that activation of this signaling pathway contributes to the hormone's cytoprotective effects in neurodegenerative processes and ischemic brain injury. At the same time, the mechanisms of melatonin's interaction with SIRT1 during inflammatory activation of astrocytes remain poorly understood and require further investigation.

Therefore, melatonin is an important regulator of circadian organization, metabolic homeostasis and neuroprotective mechanisms in the central nervous system. Modern studies demonstrate its ability to influence the functioning of mitochondria, the glymphatic system, the processes of neuroinflammation and cellular signaling, which substantiates the prospects of using this therapeutic potential.

CONCLUSIONS

It has been established that melatonin's wide range of biological effects is mediated through interactions with membrane-bound and intracellular receptors, the activation of signaling cascades, and the regulation of the expression of "clock" genes. This accounts for its role in regulating neuroendocrine, metabolic, immune, and adaptive processes, as well as in maintaining the circadian stability of the central nervous system.

Modern studies confirm the important role of melatonin in the functioning of mitochondria. The hormone contributes to the stabilization of oxidative phosphorylation processes, the preservation of the membrane potential of mitochondria, the limitation of the formation of reactive oxygen species and the inhibition of apoptotic mechanisms.

It has been been proven that melatonin reduces the intensity of neuroinflammation, suppresses the activation of astrocytes and microglia, reduces the production of pro-inflammatory cytokines, and supports the functional state of neurons in traumatic and neurodegenerative brain lesions. An important mechanism of cytoprotective action is its participation in the regulation of the glymphatic system and the elimination of neurotoxic metabolites from nervous tissue

Prospects for further research include a detailed study of the molecular mechanisms of melatonin's action in the CNS, in particular its impact on mitochondrial function, neuroinflammatory processes, SIRT1-dependent signaling pathways, and the regulation of "clock" genes. Further experimental and clinical studies are necessary for an in-depth study of the role of melatonin in the functioning of the glymphatic system, as well as substantiating the feasibility of its use in medicine as a potential therapeutic and neuroprotective agent in disorders associated with circadian disorganization, oxidative stress, and inflammatory processes.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Циркадні ритми та нейропротекторні ефекти мелатоніну в центральній нервовій системі

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Анотація. У статті узагальнено сучасні дані щодо ролі мелатоніну в регуляції циркадних ритмів та забезпеченні функціональної активності центральної нервової системи. Розглянуто основні механізми нейроендокринного контролю секреції мелатоніну, роль супрахіазматичного ядра гіпоталамуса й епіфіза у підтриманні добової ритмічності організму. Висвітлено сучасні уявлення про рецепторні механізми дії мелатоніну та особливості функціонування MT1- і MT2-рецепторів у структурах головного мозку. Поряд із хронобіологічними ефектами мелатонін бере участь у механізмах захисту клітин. Проаналізовано значення мелатоніну як ендогенного антиоксиданта та модулятора клітинних сигнальних процесів. Особливу увагу приділено його участі у регуляції функціонального стану мітохондрій, підтриманні процесів окисного фосфорилювання, контролі оксидативного стресу та забезпеченні клітинного гомеостазу. Наведено дані щодо участі мелатоніну у функціонуванні глімфатичної системи мозку, елімінації нейротоксичних метаболітів та підтриманні метаболічної рівноваги в нервовій тканині. Проведено аналіз результатів досліджень, які підтверджують нейрозахисні та протизапальні ефекти мелатоніну при ураженнях центральної нервової системи. Накопичені експериментальні та клінічні відомості підтверджують перспективність подальшого вивчення мелатоніну як біологічно активної молекули з широким спектром впливу на організм.

Ключові слова: циркадні ритми; центральна нервова система; мелатонін; нейропротекція; мітохондрії; антиоксидантна активність.

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Morphological features of the prostate gland under conditions of iodine deficiency and iodine deficiency combined with the goitrogenic substances during postnatal ontogenesis

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Abstract. According to data from the World Health Organization, pathological conditions caused by iodine deficiency rank third place of the most common non-infectious human diseases. The aim of the study was to determine the morphofunctional changes in the prostate gland over time at 60 and 90 days of iodine deficiency combined with the consumption of goitrogenic substances during postnatal ontogenesis. The experiment was conducted on 78 white inbred male rats of both prepubertal and pubertal ages. Eleven animals from each age group constituted Group 1 (control), while 14 animals were included in experimental groups 2 and 3 with simulated iodine deficiency. Experimental Groups 4 and 5 experimental groups consisted of animals from both age groups in which combined iodine deficiency with goitrogen consumption was simulated. Material for light and electron microscopy were collected on days 60 and 90 of the experiment. From a morphological view, the structural changes observed in the prostate gland involve several levels. First, due to reduced thyroid stimulation, changes in the metabolic activity of the epithelial cells of the gland's acini and ducts were noted. Second, endocrine imbalance altered the ratio of epithelial to stromal components. Third, since the prostate gland is sensitive to the interaction of androgens, estrogens, thyroid hormones, and pro-inflammatory mediators, the combined effect of iodine deficiency and goitrogenic agents manifested as inflammatory and dystrophic changes, specifically alterations in epithelial cell height, acinar lumen width, the stroma-to-parenchyma ratio, the presence of edema, and cellular infiltration. Thus, iodine deficiency and goitrogenic agents can alter thyroid homeostasis, and the thyroid axis is associated with the function and pathological conditions of the prostate gland. Thus, tth key components of thyroid signaling are detected in the prostate gland, indicating a possible direct effect of thyroid hormones on this organ. Edematous changes in the epithelium of the terminal secretory units result from ischemia caused by edematous processes in the walls of blood vessels and connective tissue elements of the prostate.

Keywords: laboratory animals; experiment; prostate; morphology; morphometry; age; ontogenesis.

INTRODUCTION

According to the World Health Organization, iodine deficiency pathologic conditions take the third place in the list of the none infectious human diseases [1]. Iodine deficiency states are considered the most widespread syndromic lesions of a non-infectious nature throughout the world [2–4]. A third of the Earth's population belongs to the group of risk and is a real target for the iodine deficiency diseases development. Insufficient intake of iodine, which acts as the main component for the formation of thyroid hormones, leads to hypothyroxinemia, which leads to a whole spectrum of disorders of the organs and systems of the body [5–7]. Iodine deficiency is a frequent environmental phenomenon that occurs as a result of a lack of iodine in the soil, food products of plant and animal origin, produced in the region of residence [8]. The problem of iodine deficiency is related not only to its tun away

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by water carried by streams of mountain rivers into the ocean [9], but also to improper soil treatment, application of herbicides, pesticides, overloading with salts of heavy metals, and other pollutants of industrial production [10]. A study of the thyroid gland of people from endemic areas shows that there are changes in the gland tissue that indicate the influence of other stromogenic factors and the body's adaptation to their influence, and some age-related features are also characteristic of the second type of changes [11].

Traditionally, iodine deficiency is studied exclusively through the prism of pathologies of the thyroid gland (goiter, hypothyroidism). However, recent decades prove that the prostate gland is an active extrathyroid store of iodine. It has its own sodium iodide symporters and uses molecular iodine as a powerful antioxidant and cell cycle regulator [12, 13]. Without proper antioxidant support of iodine in prostate tissue, lipid peroxidation is triggered, leading to chronic aseptic inflammation.

The research is very actual, as it solves an important medical and biological task: it reveals deep, previously unstudied morphological mechanisms of prostate gland damage under the conditions of the combined effect of environmental and endocrine factors (iodine deficiency and the influence of goiterogens), which will allow optimizing strategies for preserving male reproductive health.

The aim of the study: to determine the morphologica; and functional changes in the prostate gland in the dynamics from 60 to 90 days of iodine deficiency combined with the consumption of stromogens in postnatal ontogeny, taking into account age characteristics.

MATERIALS AND METHODS

In the experiment took part 78 white outbred male rats, 39 of which were sexually immature animals (3–5 months) and sexually mature rats (6–8 months). 11 animals of both age groups coplete 1 control group control, 14 animals in experimental 2nd group and experimental 3d group were with simulated iodine deficiency. The 4th and 5th experimental groups included sex mature and sex immature rats of both age groups. Animals of these groups were with simulated iodine deficiency and with the consumption of stromogens [14]. All manipulations with rats were carried out in compliance with the humane care rules with animals. The material of the prostate gland for light and electron microscopic examinations was carried out on the 60th and 90th day of the experiment. Morphometrical investigation, biochemical study and statistical data processing was also used [15].

RESULTS AND DISCUSSION

Thyroid status of prepubertal animals in Group 1: Thyrotropin (0.10±0.01) mIU/mL (p<0.01), Triiodothyronine (3.63±0.12) nmol/L (p<0.01), Thyroxine (75.44±4.01) nmol/L (p<0.01); in sexually mature animals – Thyrotropin (0.08±0.00) μIU/mL (p<0.01), Triiodothyronine (2.79±0.15) nmol/L (p<0.01), Thyroxine (55.18±2.72) nmol/L (p<0.01), respectively. Cholesterol levels within the age-normal range are: in immature animals (1.60±0.05) mmol/L (p<0.01); in mature rats (1.40±0.09) mmol/L (p<0.01). Ioduria in sexually immature rats of control group was (97.13±5.40) μg/L, and in mature rats it was (101.06±3.44) μg/L (p<0.01).

Thyroid status of prepubertal animals in Group 2: Thyrotropin (0.17±0.02) mIU/mL (p<0.01), Triiodothyronine (3.46±0.36) nmol/L (p<0.01), Thyroxine (75.49±9.60) nmol/L (p<0.01); in mature rats – Thyrotropin (0.12±0.01) μIU/mL (p<0.01), Triiodothyronine (2.97±0.37) nmol/L (p<0.01), Thyroxine (67.49±8.25) nmol/L (p<0.01), respectively. Cholesterol levels on 60th day of the experiment were: in immature sexually animals (1.63±0.17) mmol/L (p<0.01); in sexually mature animals (1.39±0.12) mmol/L (p<0.01). Ioduria in immature rats of second group was (2.73±0.29) μg/L, and in mature ratsit was (3.77±0.34) μg/L (p<0.01).

At this stage of the experiment, edema is observed in the connective tissue elements of the stroma and in the walls of blood vessels in all lobes of the prostate gland (Fig. 1). The epithelial cells of the terminal secretory portions have vacuolated cytoplasm in the apical pole and basophilia of the basal poles. Blood vessels are surrounded by edematous connective tissue fibers and amorphous stromal material.

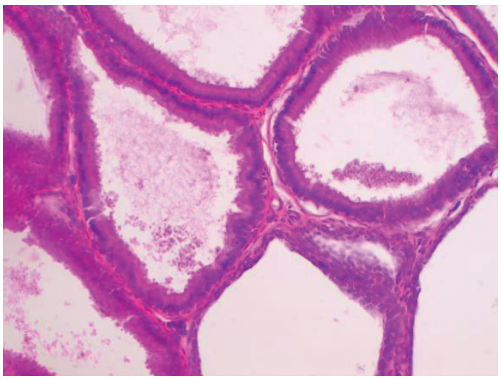

Fig. 1. Structural organization of the prostate gland of a sexually mature animal on the 60th day of iodine deficiency. Staining with hematoxylin and eosin. x200.

Electron microscopy reveals euchromatin and a thin line of heterochromatin in the nuclei. The canals of the granular endoplasmic reticulum are dilated, and the cisternae of the Golgi apparatus are also dilated and fill the cytoplasm unevenly. The mitochondrial matrix is of low electron density, and the cristae are disorganized. Secretory granules, which are localized in the cytoplasm, are of various shapes and sizes.

The height of the epithelium in the terminal secretory sections of the ventral, dorsal and coagulated lobes of the gland in immature animals increased by 0.3 % ($p<0.05$), 0.7 % ($p<0.05$), and 0.9 % ($p<0.05$), respectively. In these lobes of the prostate gland of sexually mature animals, the height of the epithelium increased by 0.2 % ($p<0.05$), 0.4 % ($p<0.05$), and 0.9 % ($p<0.05$), respectively.

Thyroid status of immature animals in group 3: Thyrotropin (0.16±0.02) mIU/mL ($p<0.01$), Triiodothyronine (3.47±0.39) nmol/L ($p<0.01$), Thyroxine (51.31±6.53) nmol/L ($p<0.01$); in sexually mature rats – Thyrotropin (0.23±0.03) μIU/mL ($p<0.01$), Triiodothyronine (2.43±0.29) nmol/L ($p<0.01$), Thyroxine (54.91±7.05) nmol/L ($p<0.01$), respectively. Cholesterol levels on 90th day of the experiment were: in immature sexually animals (1.66±0.20) mmol/L ($p<0.01$); in mature animals (1.44±0.16) mmol/L ($p<0.01$). Ioduria in sexually immature rats of third group was (1.89±0.24) μg/L, and in mature rats it was (2.29±0.21) μg/L ($p<0.01$).

The epithelium of the secretory portions of all lobules of the prostate gland is edematous. The nuclei have indistinct boundaries. The cytoplasm is stained eosinophilic. Edematous connective tissue fibers, amorphous substance, and smooth muscle cells of the gland stroma are visible. Similar edematous changes occur in the walls of blood vessels.

Submicroscopically, light colour cytoplasm of epithelial cells is observed. The tubules of the granular endoplasmic reticulum are dilated, and the Golgi apparatus is represented by deformed vesicles and cisterns. Mitochondria are visible with disorganized cristae and a light dense matrix (Fig. 2).

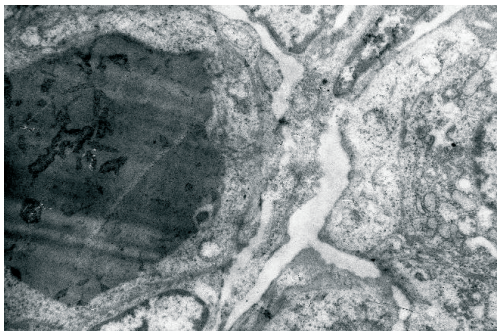

Fig. 2. Structure of the prostate gland of a sexually immature animal on the 90th day of iodine deficiency. x4800.

The height of the epithelium in the terminal secretory portions of the ventral and dorsal lobes and the coagulation gland in immature animals increased by 3.6 % ($p<0.05$). In the mentioned lobes of the prostate gland of sexually mature animals, the height of the epithelium increased by 1.1 % ($p<0.05$), 0.9 % ($p<0.05$), and 1.4 % ($p<0.05$), respectively.

Thyroid status of immature animals in group 4: Thyrotropin (0.18±0.02) mIU/mL ($p<0.01$), Triiodothyronine (3.44±0.36) nmol/L ($p<0.01$), Thyroxine (74.40±7.10) nmol/L ($p<0.01$); in sexually mature rats – Thyrotropin (0.14±0.01) μIU/mL ($p<0.01$), Triiodothyronine (2.39±0.24) nmol/L ($p<0.01$), Thyroxine (63.60±7.46) nmol/L ($p<0.01$), respectively. Cholesterol levels on 60th day of the experiment were: in sexually immature rats (1.66±0.19) mmol/L ($p<0.01$); in mature animals (1.44±0.15) mmol/L ($p<0.01$). Ioduria insexually immature rats of second group was (1.42±0.16) μg/L, and in sexually mature rats it was (1.92±0.21) μg/L ($p<0.01$).

The lumen of the terminal secretory compartments of the prostate lobules contains a homogeneous substance. The epithelial cells have basally located nuclei, the aggregate of which forms a basophilic band. The cytoplasm is eosinophilic with marked clearing at the apical pole. Blood vessels are surrounded by swollen connective tissue fibers and amorphous stromal material. The height of the epithelium in the terminal secretory sections of the ventral and dorsal lobes and the coagulation gland in sexually immature animals increased by 0.5 % ($p<0.05$), 0.9 % ($p<0.05$), and 1.1 % ($p<0.05$), respectively. In the specified regions of the prostate gland of sexually mature animals, the height of the epithelium increased by 0.3 % ($p<0.05$), 0.5 % ($p<0.05$), and 1.0 % ($p<0.05$), respectively.

Ultrastructural examination revealed the presence of euchromatin and heterochromatin in the nuclei of epithelial cells, with heterochromatin concentrated beneath the nucleolus. The tubules and canals of the granular endoplasmic reticulum, as well as the vesicles and vacuoles of the endoplasmic reticulum, are dilated. Myelin-like bodies are visible. The sarcoplasm of smooth muscle cells has a fine-grained structure, with prominent rounded mitochondria having a clear matrix (Fig. 3).

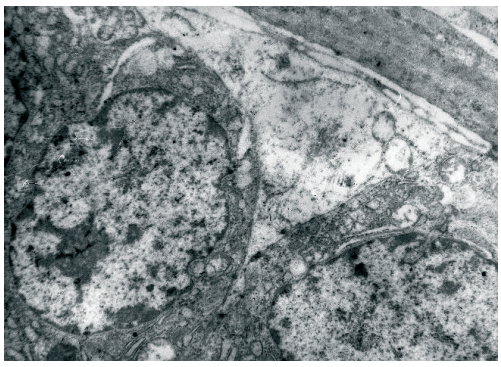

Fig. 3. Ultrastructure of the prostate gland of a sexually mature animal on the 90th day of iodine deficiency with stromogens. x4800.

Thyroid status of prepubertal animals in group 5: Thyrotropin (0.14±0.02) mIU/mL ($p<0.01$), Triiodothyronine (3.36±0.33) nmol/L ($p<0.01$), Thyroxine (50.14±5.73) nmol/L ($p<0.01$); in sexually mature rats – Thyrotropin (0.26±0.02) μIU/mL

(p<0.01), Triiodothyronine (2.06±0.18) nmol/L (p<0.01), Thyroxine (50.88±5.69) nmol/L (p<0.01), respectively. Cholesterol levels on 90th day of the experiment were: in sexually immature rats, (1.68±0.15) mmol/L (p<0.01); in mature animals (1.49±0.14) mmol/L (p<0.01). Ioduria in sexually immature animals of third group was (0.92±0.08) μg/L, and in sexually mature rats it was (1.54±0.140 μg/L (p<0.01).

Edematous changes are observed in the prostate lobes on day 90 of the experiment. Connective tissue fibers and smooth stromal myocytes are edematous, and lymphocytic infiltration is present. The walls of blood vessels are thickened, and stasis is observed in the lumen. Epithelial cells of the terminal secretory units show edema. There is a noticeable lightening of the basal poles of the cytoplasm with nuclear displacement. The apically lightened cytoplasm forms a veil-like contour of the lumen of the terminal secretory units (Fig. 4).

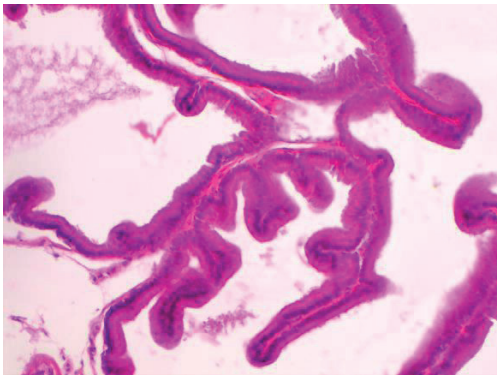

Fig. 4. Structural organization of the prostate gland of a sexually immature animal on the 90th day of iodine deficiency with stromogens. Staining with hematoxylin and eosin. x200.

The height of the epithelium in the terminal secretory sections of the ventral and dorsal lobes and the coagulation gland in immature animals increased by 3.7 % (p<0.05), 4.3 % (p<0.05), and 3.9 % (p<0.05), respectively. In the mentioned lobes of the prostate gland of sexually mature animals, the height of the epithelium increased by 1.2 % (p<0.05), 1.1 % (p<0.05), and 1.6 % (p<0.05), respectively.

Ultrastructural examination reveals deformed nuclei in the epithelial cells due to invagination of their nuclear envelope. Membrane organelles are enlarged and vacuolated. Mitochondria are visible with a lightened matrix and deformed cristae. There is stasis in the lumen of blood vessels. The cytoplasm of endothelial cells is vacuolated. Paravascular edema is evident. The sarcoplasm of smooth muscle cells has a homogenized-granular appearance.

Iodine is an essential trace element required for the synthesis of thyroid hormones, and disruptions in its intake are considered one of the causes of changes in thyroid function [16, 17]. In the current literature, iodine deficiency is described not only as a problem of endemic goiter but as a systemic factor capable of altering metabolic, endocrine, and regulatory processes in the body [5]. For experimental studies of the prostate gland, it is particularly important that thyroid status influences growth, differentiation, metabolism, and cellular interaction with the hormonal microenvironment. Thus, iodine deficiency can be considered a primary factor that, through changes in thyroid hormone levels, potentially affects the organs of the male reproductive system.

The second key aspect of the issue is foods with goitrogenic properties. These include, in particular, plants of the Brassicaceae family, which contain glucosinolates and their derivatives. Certain metabolites of these compounds, particularly thiocyanates and goitrin, may reduce iodine uptake by the thyroid gland or interfere with the synthesis of thyroid hormones [14]. A 2024 systematic review summarizes data on the effect of Brassica vegetables on thyroid function and emphasizes that the effect depends on the type of product, quantity, method of preparation, baseline iodine status, and individual physiological characteristics [18]. Therefore, in the context of adequate iodine intake, moderate consumption of such foods is not necessarily harmful, but in the event of iodine deficiency, their effects may take on greater clinical significance.

A review of the literature published after 2016 reveals that there are very few, if any, studies that simultaneously examine iodine deficiency, the consumption of iodine-rich foods, and the morphofunctional state of the prostate gland. Therefore, the available sources should be interpreted with caution: they do not prove a direct combined effect of these two factors on the prostate, but they do provide a scientific basis for designing such an experiment. The logic of the study can be based on three links: iodine deficiency and goitrogens alter thyroid status; thyroid hormones are involved in the regulation of the prostate; the prostate is a hormone-dependent organ sensitive to changes in the endocrine and inflammatory microenvironment.

A recent review by Anguiano and colleagues supports the concept of the prostate as a target organ for thyroid hormones [19]. The authors emphasize that thyroid hormones may be associated with the growth, differentiation, and metabolic activity of prostate tissue, and the consequences of hypo- or hyperthyroidism depend on age, duration of exposure, and the experimental model. This is important for planning studies in white rats, as the prostate's response may differ in cases of acute, chronic, postnatal, or adult thyroid dysfunction. In this context, iodine deficiency

should not be considered in isolation but rather as a model that alters the body's hormonal background.

Further support for this concept comes from a randomization study by Huang et al., which analyzed genetically predicted indicators of thyroid function and the risk of benign prostate diseases [21]. The authors reported that TSH levels and hypothyroid states were associated with the risk of benign prostatic hyperplasia and prostatitis. This is not experimental evidence of the effect of iodine deficiency, but it shows that thyroid regulation may be linked to pathological processes in the prostate. For morphological studies, this provides grounds for evaluating not only the organ's mass but also the condition of the epithelium, stroma, vascular bed, signs of inflammatory infiltration, and secretory activity.

Data on the extrathyroidal effects of iodine should be considered separately. In a 2023 study by Anguiano et al., molecular iodine exhibited anti-inflammatory effects in a rat model of sex hormone-induced prostate inflammation and also influenced the viability of DU145 cells and IL-6 production [6]. These results cannot be directly extrapolated to a model of iodine deficiency, but they suggest that iodine may be involved in the regulation of oxidative stress, the inflammatory response, and proliferative activity in prostate tissue. Therefore, insufficient iodine intake could theoretically alter not only the thyroid axis but also local mechanisms of tissue reactivity.

New experimental data from 2025 also show that molecular iodine is capable of modulating the viability, invasive properties, and response of prostate cancer cells depending on androgen status and model characteristics [21, 22]. For the study of the prostate gland in white rats, these data are of secondary importance: they do not describe dietary iodine deficiency [23] and do not directly concern goitrogenic foods; however, they confirm that iodine-dependent processes may be biologically significant for prostate tissue [24]. This allows us to formulate the hypothesis that prolonged iodine deficiency, especially in combination with substances that further impair thyroid hormone synthesis, may affect the structural organization of the prostate.

From a morphological view, the expected changes may involve several levels [12, 13, 25, 26]. First, due to reduced thyroid stimulation, changes in the metabolic activity of acinar and tubular epithelial cells are possible. Second, endocrine imbalance may alter the ratio of epithelial to stromal components. Third, since the prostate gland is sensitive to the interaction of androgens, estrogens, thyroid hormones, and pro-inflammatory mediators, the combined effect of iodine deficiency and goitrogens may manifest as inflammatory or dystrophic changes. However, these statements should be presented precisely as a working hypothesis, rather than as a proven fact, since there is insufficient direct contemporary evidence for such a combination of factors.

The article, based on an experiment with white rats, emphasizes that the chosen model is a suitable experimental study. Appropriate indicators include the animal's body weight and prostate weight, the morphological state of the glandular lobes, the height of the epithelium, the lumen of the acini, the ratio of stroma to parenchyma, the condition of the blood vessels, and the presence of edema or cellular infiltration. To strengthen the evidence, a morphological analysis determining thyroid status is presented, as it is the key intermediate link between iodine deficiency, goitrogenic substances, and potential changes in the prostate.

Thus, iodine deficiency and goitrogenic products can alter thyroid homeostasis, and the thyroid axis, according to current data, is associated with the function and pathological conditions of the prostate gland. This is precisely why the experimental study of morphological changes in the prostate under conditions of isolated iodine deficiency and its combination with goitrogenic dietary factors is scientifically justified and complements current understanding of the endocrine regulation of the male reproductive system.

CONCLUSION

Main components of thyroid signaling have been identified in the prostate gland, suggesting a direct effect of thyroid hormones on this organ. Edematous changes in the epithelium of the terminal secretory units result from ischemia caused by edematous processes in the walls of blood vessels and connective tissue elements of the prostate.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Морфологічні особливості передміхурової залози в умовах змодельованого йододефіциту та йододефіциту, поєднаного зі споживанням струмогенів у постнатальному онтогенезі

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Анотація. За даними ВООЗ, патологічні стани, що викликані дефіцитом йоду, займають третє місце у списку найпоширеніших неінфекційних захворювань людини. Метою дослідження було визначити морфофункціональні зміни в передміхуровій залозі у динаміці на 60 та 90 доби йододефіциту, поєднаного зі споживанням струмогенів у постнатальному онтогенезі з урахуванням вікових особливостей. Експеримент виконано на 78 білих безпородних щурах-самцях статевонезрілого та статевозрілого віку. По 11 тварин обидвох вікових груп становили 1 групу (контроль), по 14 тварин увійшли у 2 та 3 дослідні групи зі змодельованим йододефіцитом. 4 та 5 дослідні групи становили щури обидвох вікових груп, яким моделювали поєднаний йододефіцит зі споживанням струмогенів. Забір матеріалу для світлооптичного та електронно-мікроскопічного досліджень проводили на 60 та 90 доби експерименту. З морфологічної точки зору отримані структурні зміни тканин предміхурової залози стосуються кількох рівнів. По-перше, через зниження тиреоїдної стимуляції відзначались зміни метаболічної активності епітеліальних клітин ацинусів і проток залози. По-друге, ендокринний дисбаланс змінював співвідношення епітеліального та стромального компонентів. По-третє, оскільки передміхурова залоза є чутливою до взаємодії андрогенів, естрогенів, тиреоїдних гормонів і прозапальних медіаторів, комбінований вплив йододефіциту та струмогенів проявлявся через запальні та дистрофічні зміни, зокрема зміна висоти епітеліальних клітин, просвіту ацинусів, співвідношення строми й паренхіми, наявність набряку та клітинної інфільтрації. Отже, йододефіцит і струмогенні продукти можуть змінювати тиреоїдний гомеостаз, а тиреоїдна вісь пов'язана з функціонуванням і патологічними станами передміхурової залози. Отже, у передміхуровій залозі виявляються ключові компоненти тиреоїдної сигналізації, що свідчить про можливу пряму дію гормонів щитоподібної залози на цей орган. Набрякові зміни в епітелії кінцевих секреторних відділів є наслідком ішемії через набрякові процеси у стінці кровоносних судин та сполучнотканинних елементах простати.

Ключові слова: лабораторні тварини; експеримент; передміхурова залоза; морфологія; морфометрія; вік; онтогенез.

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