UDC 616.24-002-053.2

Yu.V, Marushko, O.V. Khomych

Peculiarities of acoustic diagnostic methods in pediatric practice (literature review, own research)

Bogomolets National Medical University, Kyiv, Ukraine

Modern Pediatrics. Ukraine. (2024). 6(142): 88-95. doi: 10.15574/SP.2024.6(142).8895

For citation: Marushko YuV, Khomych OV. (2024). Peculiarities of acoustic diagnostic methods in pediatric practice (literature review, own research). Modern Pediatrics. Ukraine. 6(142): 88-95. doi: 10.15574/SP.2024.6(142).8895.

Diseases of the respiratory system are among the most common among the population of different age categories. Sound, as a physical phenomenon, is the propagation of longitudinal elastic waves in a medium, for example, in the air. Waves with frequencies below 16 Hz are called infrasound, and above 20,000 Hz are called ultrasound, and these waves cannot be perceived by the human ear. That is why the study of acoustic signals is extremely important for the diagnosis and monitoring of respiratory diseases.

The aim of this article is to investigate the features of the use of acoustic diagnostic methods in pediatric practice through the analysis of contemporary literature over the past five years, sourced from Scopus and Web of Science databases, as well as conducting original clinical research.

Results. Acoustic diagnostic methods in pediatrics have great potential due to their non-invasiveness and lack of radiation exposure. Literary sources indicate the high efficiency of these methods in detecting pathologies of the respiratory system in children, especially in the early stages of diseases. Our research with the acoustic monitoring device «Trembita—Corona» confirmed the ability to accurately determine the affected areas of the lungs with the help of highly sensitive acoustic sensors. The primary focus is paid to the comparative evaluation of the diagnostic efficacy, safety, and potential for using these methods in children of different age groups. It has been proven that acoustic methods allow the identification of pathological changes even in hard-to-reach extracostal areas. The effectiveness of the acoustic monitoring device «Trembita—Corona» developed and implemented in clinical practice is confirmed by the possibility of mathematical data processing, which significantly increases the accuracy of diagnosis, excluding the human factor. The use of acoustic methods in pediatrics opens up new opportunities for early detection and monitoring of diseases of the respiratory system.

Conclusions. The implementation of acoustic methods into clinical practice is a promising direction that deserves further research and development. The conducted experimental studies demonstrated the ability of the «Trembita—Corona» device to accurately diagnose and localize lung lesions in community-acquired pneumonia, confirming the effectiveness of the developed methods and algorithms.

No conflict of interests was declared by the authors.

Keywords: acoustic monitoring device «Trembita—Corona», community-acquired pneumonia, children, diagnostics, COVID-19.

Особливості акустичних методів діагностики в педіатричній практиці (огляд літератури та власні дослідження)

Ю.В. Марушко, О.В. Хомич

Національний медичний університет імені О.О. Богомольця, м. Київ, Україна

Захворювання дихальної системи є одними з найпоширеніших серед населення різних вікових категорій. Звук, як фізичне явище, є поширенням подовжніх пружних хвиль у середовищі, наприклад, у повітрі. Хвилі з частотами нижче 16 Гц називають інфразвуковими, а вище 20000 Гц — ультразвуковими, і вони не можуть бути сприйняті людським вухом. Саме тому дослідження акустичних сигналів є надзвичайно важливими для діагностики та моніторингу захворювань органів дихання.

Мета дослідження: вивчення особливостей застосування акустичних методів діагностики в педіатричній практиці шляхом аналізу сучасної літератури за останні п'ять років, отриманої з баз даних Scopus та Web of Science, а також проведення власних клінічних досліджень.

Результати. Акустичні методи діагностики в педіатрії мають великий потенціал через їхню неінвазивність та відсутність радіаційного впливу. Літературні джерела вказують на високу ефективність цих методів у виявленні патологій дихальної системи в дітей, особливо на ранніх стадіях хвороб. Наші дослідження пристроєм акустичного моніторингу «Trembita—Corona» підтвердили здатність точно визначати уражені ділянки легень за допомогою високочутливих акустичних сенсорів. Основну увагу приділено порівняльній оцінці діагностичної ефективності, безпечності та потенціалу використання цих методів у дітей різних вікових груп. Доведено, що акустичні методи дають змогу ідентифікувати патологічні зміни навіть у важкодоступних зареберних областях. Ефективність розробленого і впровадженого у клінічну практику пристрою акустичного моніторингу «Trembita—Corona» підтверджується його здатністю проводити математичну обробку даних, що значно підвищує точність діагностики, виключаючи людський фактор. Використання акустичних методів у педіатрії відкриває нові можливості для раннього виявлення та моніторингу захворювань дихальної системи.

Висновки. Впровадження акустичних методів у клінічну практику є перспективним напрямком, що заслуговує на подальші дослідження та розвиток. Проведені експериментальні дослідження продемонстрували здатність пристрою «Trembita—Corona» точно діагностувати та локалізувати ураження легень при позагоспітальній пневмонії, підтверджуючи ефективність розроблених методик та алгоритмів.

Автори заявляють про відсутність конфлікту інтересів.

Ключові слова: пристрій акустичного моніторингу «Trembita—Corona», позалікарняна пневмонія, діти, діагностика, COVID-19.

Intoduction

Respiratory diseases occupy a leading place in the structure of morbidity among the population of different age groups [2–4]. During auscultation, doctors detect the localization of the pathological process and, based on certain characteristics, identify the pathology. The clinical diagnosis depends on the detected auscultatory phenomena, such as rhonchi, coarse crackles, or fine crackles. According to the order of the Ministry of Health of Ukraine dated August 2, 2022 No. 1330 «Standards of medical care for community-acquired pneumonia in children», the diagnosis of community-acquired pneumonia (CAP) is established clinically, but laboratory and instrumental studies can be carried out according to individual indications. However, sometimes there are sounds that are difficult to identify due to their indistinctness and weak intensity, which causes the doctor to have doubts about determining their nature. In addition, auscultation in young children has its difficulties and limitations: young children often cry during the examination and cannot follow the doctor's instructions regarding controlled breathing. Because of these factors, there is a risk of misdiagnosis.

Acoustics is a branch of physics that studies the properties of elastic vibrations and waves in the frequency range from 0 Hz to 10^{13} Hz, their distribution, interaction with physical and biological objects, as well as the application of the knowledge obtained to solve engineering problems [5–7].

Understanding the processes of generation and propagation of waves in various environments is of key importance for many areas of human activity. That is why the scientist Bruce Lindsay created a graphic model known as «Lindsay's wheel of acoustics» [5,7]. It illustrates the relationship between various aspects of physical acoustics and human activity, demonstrating how fundamental acoustic principles are applied in various areas of life.

Lindsay's wheel of acoustics identifies four main areas: life sciences, earth sciences, arts, and engineering, where acoustic knowledge plays an important role. The medical component of this scheme includes the use of acoustic waves in the diagnosis and treatment of diseases, such as ultrasound diagnostics, which allows visualization of internal organs and body structures without invasive procedures. Acoustics in medicine contributes not only to accurate diagnosis but also to effective treatment and improvement of the general state of health of patients. In the center of this diagram are fundamental studies in the field of acoustics, which are united under the common name — physical acoustics. Thus, «Lindsey's wheel of acoustics» clearly demonstrates the significance of acoustic research for a wide range of scientific and applied problems [8–10].

Sound is a physical phenomenon characterized by the propagation of longitudinal elastic waves in the environment, in particular in the air. With a wave frequency of 16 to 20,000 Hz, these oscillations cause vibrations of the eardrum, which the human brain interprets as sound sensations. Elastic waves in any medium with frequencies in the range from 16 to 20,000 Hz are called sound waves or sound. Waves with frequencies below 16 Hz are known as infrasound, and waves with frequencies above 20,000 Hz are called ultrasound. Infrasound and ultrasound waves fall outside the range of human hearing and thus cannot be detected by the human ear [11,12].

Ultrasound is widely used in medicine as a diagnostic and therapeutic tool. In surgery, ultrasound is used due to the ability to create powerful ultrasound beams that can be focused on a certain pathological area. The ultrasound diagnostic method is characterized by minimal impact on tissues and high informativeness. Sound waves propagating in a straight line in a homogeneous medium are reflected and refracted at boundaries with different acoustic resistances. Modern methods of ultrasound research can be divided into location and translucency. This method is based on the principle that different tissues of the body have different degrees of ultrasound absorption. Thanks to this, it is possible to obtain images of the internal structures of the body with high accuracy. Locational methods use the reflection of ultrasound waves to determine the location and shape of objects inside the body, while transluminal methods involve the passage of ultrasound through tissues to study their internal structure.

Infrasound is waves with frequencies that are not perceived by the human ear, but they can affect the physiological state of a person. This effect is explained by the phenomenon of resonance since the internal organs of the body have low natural frequencies of oscillation: for the abdominal cavity and chest it is about 5 Hz and for the head — 20–30 Hz. The average resonance frequency for the whole body is about 7 Hz. The effect of infrasound on the human body can cause discomfort or physiological changes associated with resonant oscillations of internal organs [13,15].

The main characteristics of acoustic signals include:

— the amplitude of the acoustic signal is the maximum deviation of the oscillating point from its equilibrium position, it determines the intensity of the sound or its volume;

— the frequency of the acoustic signal determines the number of oscillations occurring per unit of time, and is measured in hertz (Hz);

— the average signal power determines the amount of energy carried by a sound wave through a unit of area per unit of time.

The aim of this article is to investigate the application of acoustic diagnostic methods in pediatric practice through the analysis of contemporary literature over the past five years, sourced from Scopus and Web of Science databases, as well as conducting original clinical research.

The primary focus is on the comparative evaluation of the diagnostic efficacy, safety, and potential for using these methods in children of different age groups. Materials and methods of the study include a literature review over the last five years using the Scopus and WoS databases, alongside the guidelines of the European Respiratory Society (ERS), American Thoracic Society (ATS), World Health Organization (WHO), and the latest protocols from the Ministry of Health of Ukraine.

Today, respiratory acoustics is a promising scientific field. The main tasks of this field are the creation of a theory of propagation and the generation of sounds in the lungs. The development of objective acoustic methods is also important. This can significantly improve the diagnosis of respiratory diseases [4,7,14,16].

The main tasks of respiratory acoustics are the analysis of acoustic signals to speed up the diagnosis of diseases of the respiratory system. This includes acoustic studies of coughing sounds, wheezing, and crepitations, which may indicate the presence of pathologies such as asthma or pneumonia. The use of special microphones and signal processing algorithms allows for a detailed analysis of these sounds. This helps medical professionals accurately determine the nature and extent of lung tissue damage. Thus, respiratory acoustics is a valuable tool in the early detection and monitoring of respiratory diseases.

The conventional approach to measuring acoustic signals involves using a stethoscope, which isolates sounds produced by the chest wall's vibrations and mechanically filters specific frequencies. These acoustic phenomena can be recorded for further analysis by converting the acoustic pressure into electrical signals [6,17].

In modern conditions, electronic stethoscopes occupy an important place in the field of respiratory acoustics. They are key tools for the study and analysis of respiratory sounds, providing high sensitivity and accuracy in the perception of acoustic signals. Traditional stethoscopes use analog filtering and sound amplification for their interpretation by a qualified medical professional [17,18]. Stethoscopes have two sides — a bell and a diaphragm, each of which has different frequency characteristics. The bell amplifies sounds below 112 Hz [20], providing better sound transmission at these frequencies compared to the diaphragm, which reduces low frequencies [19]. Both bells and diaphragms significantly reduce sound above 200 Hz, which limits the ability to distinguish sounds in this frequency range [1]. The sensitivity of human hearing covers the range from 20 to 20,000 Hz [21,22]. However, due to the range of the human ear to certain frequencies, larger deviations at high frequencies are required for the human ear to perceive them as different frequencies [1]. Electronic stethoscopes use various sensors, condenser microphones, and piezoelectric sensors, to convert acoustic signals into electrical ones, which are then processed and filtered. [21,22]. Compared to traditional stethoscopes, electronic ones amplify acoustic signals, decode artifacts, record them, and analyze them [20].

The introduction of electronic stethoscopes into daily medical practice faces certain difficulties. One of them is the high cost, and secondly, some models do not provide equally effective amplification of all frequencies, which can affect the correct interpretation of sound signals. However, one of the important technical characteristics of electronic stethoscopes is the ability to focus sound signals and amplify weak vibrations, which makes them effective for diagnosing various diseases.

According to Ram Mor et al., the contact microphone array provides 70% sensitivity and 80% specificity of the technique in the diagnosis of patients with pneumonia [16]. In his works, M. Kompis proposed a new method for acoustic visualization of the human respiratory system. The proposed system uses simultaneous recordings of chest sounds from several sensors and subsequent digital data processing. Sounds were recorded using 8 and 16 microphones in five patients (four healthy adult men and one child with lung consolidation). The results of laboratory studies have shown that sound sources can be localized with an accuracy of up to 2 cm. The data obtained from healthy people show clear patterns of respiratory sounds during inhalation and exhalation. In particular, the images confirm the hypothesis that inspiratory sounds are generated mainly at the periphery of the lungs, while expiratory sounds originate from the central part [9].

In pediatric pulmonology, the method of pulmophonography is used, which is based on the recording of respiratory sounds with the help of electret microphones placed above the lungs. The received sound signals are subjected to filtering and digital processing, followed by mathematical analysis. Despite the potential advantages of this method, this approach has limitations: it is able to analyze only a certain type of noise, and it also does not provide accurate localization of the source of the noise in the lungs and its positioning. These limitations complicate the widespread implementation of this method in clinical practice. However, at the current stage, the computer analysis of breathing sounds is a promising tool for diagnosing pathological processes in the lungs, which opens up new opportunities for more accurate diagnosis and monitoring of patients' condition [8,15].

The ultrasound scanning method is widely used in respiratory acoustics to diagnose pathological processes in the lungs. Diseases of the respiratory system, such as pneumonia, are often accompanied by the compaction of tissues, which makes them available for ultrasound imaging in the subpleural areas of the lungs. Pneumonia causes the formation of inflammatory infiltrates, filling of alveolar spaces with exudate, and swelling of tissues. These are the main pathological processes that lead to a decrease in the air space in the lungs. The ultrasound image of the pathological area reveals an irregularly shaped zone with decreased echogenicity and indistinct borders in the early stage of the disease, enabling accurate diagnosis at an early stage.

Ultrasound diagnostics of the chest organs has several significant disadvantages. Firstly, it is characterized by insufficient information due to the limited ability of ultrasound to penetrate through the minimal layer of lung tissue between the pneumonic focus and the chest wall, which leads to the fact that inflammation may remain invisible in the image. Secondly, foci of inflammatory processes located deep in the lung tissue are often inaccessible for visualization, which makes it difficult to assess the areas of infiltration. The third limitation is the need for specialized skills to perform the study and correctly interpret the results, which require practical experience and professional training. Taking into account these aspects, it can be concluded that ultrasound diagnostics is not the most effective method of examining children with suspected pneumonia, due to its limited informativeness and the requirement for specialized skills of the operator.

The method of passive echolocation is a modern technique of examining the respiratory system, which is used to detect auscultatory sounds with the help of special equipment and a virtual model. This method is based on the analysis of acoustic waves generated by respiratory processes and their comparison with the standard stored in the database of the diagnostic system. The advantages of the method include its safety and non-invasiveness, as it does not require radiation and does not require the use of breathing masks. This makes it especially useful for patients of all ages, including newborns and those in the unconscious state, where other methods may be difficult or impossible to use. However, the method has its limitations. For example, it is sensitive to external noise and interference, which can affect the accuracy of the acoustic analysis and lead to inaccurate results. In addition, for effective work, complex mathematical processing of the received data is required, as well as synchronization between sensors to accurately determine the location of the source of auscultatory noises. An additional challenge is the need for a developed database for correct comparison and analysis of received signals [1,21].

Therefore, although the method of passive echolocation is promising in the diagnosis of pathological lung conditions using acoustic data, its application requires a complex approach and specialized training to achieve the best results [15].

Computer phonospirography is a method used in pulmonology to visualize additional sounds above the lungs by analyzing two-dimensional phonospirograms and determining the time of a complete respiratory cycle. Electronic auscultation, which is carried out using only 4 fixed sensors, ensures diagnostic accuracy by standardizing the procedure and limiting the variability of results.

Fig. 1. Scheme of positioning of the pathological process when using the acoustic monitoring device «Trembita—Corona»: 1 — first listening point; 2 — pair of receivers; 3 — line connecting the patient's clavicles at two listening points; 4 — second listening point; 5 — pathological process

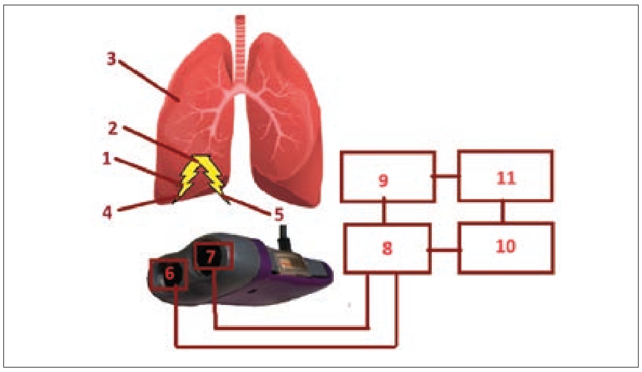

Fig. 2. Functional diagram of the «Trembita—Corona» device: 1 — lungs; 2 — affected areas generating acoustic vibrations; 3 — chest wall; 4,5 — acoustic waves propagating through the chest; 6,7 — acoustic sensors of the «Trembita—Corona» device; 8 — matching and conversion unit; 9 — microprocessor unit for signal analysis; 10 — positioning unit for locating acoustic vibration sources; 11 — operational indication unit for data visualization and interpretation

This method also has its limitations. The patient must stand or sit during the examination, which makes it unsuitable for recumbent patients. Deciphering the results is performed by the doctor, which can affect the objectivity of the interpretation. The repeated use of sensors complicates the application of the method in the context of the COVID-19 pandemic due to the need to comply with strict hygiene standards. One of the serious limitations is the low mobility of the device due to its large dimensions, which limits its use in conditions of limited space or in mobile medical teams [12,13,15].

The creation of a fully automated system for monitoring and analyzing breathing noises is a modern challenge in medical science. The importance of this task is especially relevant in connection with the need for early diagnosis of inflammatory processes in the lungs, which can be detected using the acoustic method. This becomes key in cases of asymptomatic course of the disease or in cases where the lesion is in hard-to-reach areas behind the rib.

Together with specialists of the National Aviation University, a team of leading specialists of the Bogomolets National Medical University has developed a device for acoustic monitoring «Trembita—Corona», designed to evaluate acoustic signals above the surface of the lungs [12,13,15,18].

The proposed control method is based on the recording and analysis of acoustic signals, which is carried out using a combination of two receivers. After processing the received signals, a detailed analysis of their main acoustic characteristics and determination of the direction and position of the source of these vibrations is carried out by the method of acoustic triangulation.

This allows you to accurately determine the location of pathological lung lesions, including those located behind the rib. Using this method makes it possible to promptly assess the general condition of the lungs and to localize pathological changes in real time. On the diagram of the positioning of the pathological process presented in Fig. 3, it is shown how the double receivers are located parallel to the line that connects the patient's clavicles at the points being studied.

Fig. 1 shows the localization of the pathological process (5) during listening using a pair of receivers (2). These receivers are located parallel to the line (3) connecting the patient's clavicles at two listening points (1,4). This configuration allows you to accurately determine the localization of the pathological process (5) in the lungs by means of acoustic triangulation. The hearing is conducted to obtain detailed information about the nature and distribution of pathological changes in the relevant areas. This method allows you to identify lesions, even if they are located in areas of the lungs that are difficult to listen to [12,13,15].

Fig. 2 shows the functional diagram of the device for acoustic monitoring of the lungs «Trembita—Corona», which is able to identify and localize affected areas, including areas located behind the ribs.

The functional diagram shows how, when the lungs (1) work, the affected areas (2) generate acoustic vibrations that propagate through the chest (3). The spectrum of these fluctuations depends on the respiratory parameters and the

Table

Distribution of patients by age and gender

Indicator	Group I, community-acquired pneumonia, n=60	Group II, healthy children, n = 60
Age, years	3.5±0.3	4.1±0.5
The number of boys	35 (58.33%)	21 (35%)
The number of girls	25 (41.67%)	39 (65%)

state of the lungs. These oscillations create acoustic waves (4, 5).

The acoustic sensors of the «Trembita—Corona» device (6, 7) capture acoustic vibrations (4, 5) and convert them into electrical analog signals, which are transmitted to the matching and conversion unit (8). The microprocessor unit analyzes acoustic signals (9). The positioning unit (10) superimposes the received information on the coordinate diagram, determining the location of the source of acoustic vibrations, and transmits this information to the operational indication unit (11).

The «Trembita—Corona» device is equipped with an automated system for monitoring and evaluating respiratory noises, which eliminates the influence of the human factor and allows for mathematical data processing.

The authors of the article conducted the study using the «Trembita—Corona» device from September 1, 2020, to January 31, 2024. During the study, 120 children (56 boys and 64 girls) aged between 1 month and 6 years were examined. They received treatment in the pediatric departments of Children's Clinical Hospital No. 5, participated in the study. The children were divided into two groups: the Group I included 60 patients diagnosed with community-acquired pneumonia (CAP), while the Group II consisted of 60 healthy children. The distribution by age and gender is given in the table.

Children were assessed in accordance with the established protocol. Patients of the Group I were diagnosed with CAP based on the evidence-based clinical guideline «Pneumonia in children» (Clinical Guideline 2022–1380 dated August 2, 2022) and the Standards of Medical Care for «Community-Acquired Pneumonia (CAP) in children» (SMC 2022–1380, dated August 2, 2022). *The inclusion criteria* for the first group were as follows: children aged 1 month to 6 years; CAP verified through anamnestic, clinical, laboratory and radiographic data; and informed consent from the parents or guardians of the child. *The exclusion criteria* for the study included chronic bronchopulmonary diseases, cystic fibrosis, congenital and hereditary bronchopulmonary disorders.

Using «Trembita–Corona», all patients had a study of the average signal power, frequency, and amplitude of the acoustic signal in 12 octaves. The acoustic spectrum was divided into two parts: the low-frequency range (from 0.1 Hz to 200 Hz)up to and including the fourth octave, and a high-frequency range (from 200 Hz to 5 kHz) from the fifth to the twelfth octave.

The most promising is the selection of the pathological process of lung damage in CAP in the ranges of 0, 1, 2, 3, 4, 5, 6, 7, 8 octaves by comparing the average signal power ($p<0.001$) in children with CAP and healthy children.

A detailed analysis revealed a pathological process at the maximum level of signal power directly in the places where the measurements were taken. However, at all points of the acoustic monitoring of the lungs, an acoustic signal corresponding to the lesion of this part of the lungs was detected, and the frequency spectrum of this signal was clearly defined. This confirms the effectiveness of the proposed method of automated computer monitoring and localization of lung damage zones in CAP and also opens new perspectives for the development of automated diagnostic systems.

The use of acoustic diagnostic methods in pediatric practice has significant potential due to their non-invasiveness and lack of radiation exposure. Literary sources testify to the high efficiency of such methods in detecting pathologies of the respiratory system in children, especially in the early stages of the disease. Our research has confirmed the possibility of accurately determining the affected areas of the lungs with the help of highly sensitive acoustic receivers. In particular, it was established that acoustic methods allow the detection of pathological changes even in hard-to-reach extracostal areas. The effectiveness of the acoustic monitoring device «Trembita—Corona» developed and put into practice is confirmed by the possibility of mathematical data processing, which significantly increases the accuracy of diagnostics, without the use of the human factor. The use of acoustic methods in pediatrics opens new horizons for early detection and monitoring of diseases of the respiratory system, ensuring high informativeness and safety for patients.

Conclusions and prospects for further research

1. The introduction of acoustic methods into clinical practice is a promising direction that deserves further research and development.

2. The conducted experimental studies demonstrated the ability of the «Trembita—Corona» device to accurately diagnose and localize lung lesions in CAP, confirming the effectiveness of the developed methods and algorithms.

3. Improvement of the methods of diagnosing CAP in preschool children using the «Trembita—Corona» device made it possible to reveal significant differences between healthy children and patients with CAP, which opens new perspectives for further scientific research.

Funding. This study did not receive any external funding.

No conflict of interests was declared by the authors.

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Відомості про авторів:

Марушко Юрій Володимирович — д.мед.н., проф., зав. каф. педіатрії ПО НМУ ім. О.О. Богомольця. Адреса: м. Київ, бульв. Т. Шевченка, 13; тел.: +38 (044) 234-40-62. https://www.scopus.com/authid/detail.uri?authorId=57375654800. https://publons.com/researcher/3152282/yuriy-marushko/. https://orcid.org/0000-0001-8066-9369.
Хомич Ольга Вікторівна — PhD, асистент каф. педіатрії ПО НМУ ім. О.О. Богомольця. Адреса: м. Київ, бульв. Т. Шевченка, 13; тел.: +38 (044) 234-40-62. https://www.scopus.com/authid/detail.uri?authorId=57221595866. https://www.webofscience.com/wos/author/record/ABC-3924-2020. https://orcid.org/0000-0001-9272-7159.
Стаття надійшла до редакції 02.07.2024 р., прийнята до друку 15.10.2024 р.