DOI: https://doi.org/10.17816/DD632499

Digital stethoscope: a new era of auscultation

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ABSTRACT

The article reviews modern electronic and digital stethoscopes. The publications of the last 10 years were analyzed using eLIBRARY.ru, PubMed, Google Scholar with “аускультация” (“auscultation”), “электронный стетоскоп” (“electronic stethoscope”), “цифровой стетоскоп” (“digital stethoscope”), and “телемедицина” (“telemedicine”) keywords. New ways to auscultate using digital stethoscopes were considered. Products from the most popular manufacturers were briefly characterized. Improved functionality and versatility of a digital stethoscope (ability to evaluate heart, lung, bowel, and other organ sounds), noise reduction and sound filtering make digital stethoscopes an even more attractive tool. If these challenges are met, a digital stethoscope will undoubtedly become an indispensable tool in the diagnosis, monitoring and treatment of diseases and in patient self-monitoring. Telemonitoring of patients with cardiovascular and respiratory diseases is a promising area of application for modern models of digital stethoscopes. Auscultation is especially important to evaluate changes during long-term follow-up, for early detection of complications and decompensated chronic non-infectious diseases such as chronic obstructive pulmonary disease, asthma, myocardial infarction, etc.

Keywords: auscultation; electronic stethoscope; digital stethoscope; telemedicine.

To cite this article:

Garanin AA, Aydumova OYu, Rubanenko AO, Bibikova EG. Digital stethoscope: a new era of auscultation. *Digital Diagnostics.* 2024;5(4):808–818. DOI: https://doi.org/10.17816/DD632499

Received: 22.05.2024 **Accepted:** 06.06.2024 **Published online:** 05.11.2024

DOI: https://doi.org/10.17816/DD632499

Цифровой стетоскоп — новая эра аускультации

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АННОТАЦИЯ

В статье представлен обзор современных электронных и цифровых стетоскопов. Проведён анализ публикаций за последние 10 лет с использованием поисковых систем eLIBRARY.ru, PubMed, Google Scholar по ключевым словам: «аускультация», «электронный стетоскоп», «цифровой стетоскоп», «телемедицина». Рассмотрены новые возможности аускультации при использовании цифровых стетоскопов. Даны краткие характеристики изделий наиболее востребованных на рынке производителей. Повышение функционала и универсальности цифрового стетоскопа (возможность анализировать звуки сердца, лёгких, кишечника и других органов), а также улучшение шумоподавления и фильтрации полученного звука позволят сделать цифровые стетоскопы ещё более привлекательными для использования. По мере решения этих задач цифровой стетоскоп определённо станет незаменимым инструментом в диагностике, мониторинге и лечении заболеваний, а также самоконтроле пациентов. Перспективным направлением использования современных моделей цифровых стетоскопов является телемониторинг пациентов с заболеваниями сердечно-сосудистой и дыхательной систем. Особенно важна оценка аускультативной картины пациентов в динамике, при длительном наблюдении, что может способствовать раннему выявлению осложнений и декомпенсаций различных хронических неинфекционных заболеваний, например хронической обструктивной болезни лёгких, бронхиальной астмы, инфаркта миокарда и т.д.

Ключевые слова: аускультация; электронный стетоскоп; цифровой стетоскоп; телемедицина.

Как цитировать:
Гаранин А.А., Айдумова О.Ю., Рубаненко А.О., Бибикова Е.Г. Цифровой стетоскоп — новая эра аускультации // Digital Diagnostics. 2024. Т. 5, № 4. С. 808–818. DOI: https://doi.org/10.17816/DD632499

Рукопись получена: 22.05.2024 **Рукопись одобрена:** 06.06.2024 **Опубликована online:** 05.11.2024

ЭКО•ВЕКТОР

DOI: https://doi.org/10.17816/DD632499

数字听诊器 — 听诊新时代

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摘要

本文对现代电子和数字听诊器进行了概述。文章通过eLIBRARY.ru、PubMed、Google Scholar等搜索引擎，以 “听诊”、“电子听诊器”、“数字听诊器”、“远程医疗” 为关键词，对过去10年的发表文章进行了分析。 研究了使用数字听诊器进行听诊的新的可能性。给出了市场上最受欢迎的制造商的产品简介。数字听诊器功能的增强和多功能性（能够分析心脏、肺、肠和其他器官的声音），以及改进降噪和对接收声音的过滤，将使数字听诊器更具使用吸引力。随着这些挑战的解决，数字听诊器必将成为疾病诊断、监测、治疗，以及患者自我监控不可替代的工具。对心血管和呼吸系统疾病患者进行远程监控是使用现代数字听诊器的一个很有前景的发展方向。尤其重要的是，在长期随访过程中对患者的听诊情况进行动态评估，这有助于及早发现各种慢性非传染性疾病的并发症和失代偿，如慢性阻塞性肺病、支气管哮喘、心肌梗死等等。

关键词：听诊；电子听诊器；数字听诊器；远程医疗。

引用本文：
Garanin AA, Aydumova OYu, Rubanenko AO, Bibikova EG. 数字听诊器 — 听诊新时代. *Digital Diagnostics.* 2024;5(4):808–818. DOI: https://doi.org/10.17816/DD632499

收到：22.05.2024 **接受：**06.06.2024 **发布日期：**05.11.2024

INTRODUCTION

auscultation of sound phenomena accompanying the functioning of internal organs is one of the most important stages of the objective examination of a patient. Indirect auscultation has been used for almost 200 years, since the invention of the first stethoscope by Laennec in 1816. The funnel with a membrane he introduced made it possible to amplify the volume of sound signals. In 1940, Rappaport and Sprague improved the design of the stethoscope by proposing a dual-head configuration combining a bell and a diaphragm [1]. For a long time, the stethoscope remained unchanged in form.

The simplicity of use, cost-effectiveness, and wide availability make the classical stethoscope a popular tool among healthcare professionals [2]. It should be noted that, despite the simplicity and reliability of the classical auscultation method, it has a number of limitations. First and foremost are the distortions of transmitted sound signals caused by the acoustic properties of the stethoscope head, the flexibility of the tubing walls, and individual patient characteristics (chest wall thickness). In addition, sound perception is subjective and depends on the age and experience of the examiner [3, 4]. Finally, classical auscultation does not allow other specialists to analyze the detected sounds without direct patient presence, and the resulting data cannot be stored or reviewed [5]. This creates challenges in consulting patients using telemedicine technologies, as well as in remote monitoring and interpretation of physical examination findings in controversial clinical situations or legal proceedings [6].

The COVID-19 pandemic also highlighted the need to develop a new approach to auscultation using stethoscopes that can provide remote monitoring and minimize the risk of infection for healthcare workers during patient examination [7].

Electronic Stethoscope

New opportunities for auscultation emerged with the development of the electronic stethoscope. An electronic stethoscope consists of three modules providing for data acquisition, preprocessing, and signal transformation. The data acquisition module performs filtering, buffering, and amplification of the auscultated sounds, and converts the acoustic signal into a digital one. The preprocessing module filters the signal and removes artifacts. The signal transformation module then clusters the data for clinical decision-making [8].

Several types of electronic stethoscope sensors are distinguished based on the mechanism used to convert sound into an analog electrical signal.

Dual-diaphragm sensor: sound vibrations are captured by the stethoscope diaphragm and transmitted to a diaphragm within the microphone. However, the two diaphragms, separated by an air channel, may lead to excessive amplification of ambient noise and inaccurate transmission of the sound signal.

Piezoelectric sensor: sounds captured by the diaphragm alter the structure of a crystalline substance, converting the sound signal into an electrical signal.

Microelectromechanical system. The diaphragm of the stethoscope is located in a nominal capacitance field, which changes in accordance with the pressure of the sound wave. This change in capacitance converts the sound signal into an electrical one [9, 10].

Environmental noise suppression is also a critical function of the electronic stethoscope. Cain et al. [11] tested electronic stethoscopes in simulated helicopter noise conditions at 70–100 dB to determine the noise threshold for auscultation of heart and lung sounds. The noise threshold was 85 dB for heart tones and 75–80 dB for breath sounds. This implies the need for a signal-to-noise ratio improvement of at least 30 dB, which can be achieved by enhanced noise suppression. This would allow electronic stethoscopes to be used during natural disasters and patient transportation. This problem has been addressed using a digital filter capable of isolating the desired frequency range from the signal [1, 2]. The sound phenomena of internal organ function span different frequency ranges. Existing digital stethoscopes offer adjustable frequency modes for optimal auscultation of specific sounds, such as breath or heart sounds. For instance, the Welch Allyn Elite™ electronic stethoscope (Welch Allyn, USA) uses a 20–420 Hz frequency mode for heart auscultation and a 350–1900 Hz mode for lung auscultation. Thus, electronic stethoscopes enhance both sound quality and volume. The 3M™ Littmann® CORE stethoscope (3M, USA) with a piezoelectric sensor amplifies sound up to 40 times, whereas the Thinklabs One™ stethoscope (Thinklabs, USA) with a MEMS sensor amplifies sound up to 100 times [12, 13].

Undoubtedly, the electronic stethoscope increases the diagnostic value of auscultation [14]. In 2016, Azimpour et al. [15] investigated the potential of using an electronic stethoscope for acoustic diagnosis of hemodynamically significant (>50%) coronary artery stenosis by detecting intracoronary murmurs caused by turbulent blood flow within the artery in the presence of such stenosis. The coronary anatomy, as well as the presence and severity of atherosclerotic lesions, were verified using coronary angiography. The sensitivity and specificity of coronary artery stenosis detection by auscultation using an electronic stethoscope were 70% and 80%, respectively ($p < 0.001$). Several electronic auscultation test systems have been proposed for detection of obstructive coronary artery disease: CSA SonoMedica model 3.0™ (SonoMedica, USA), CADence Ironman™ (AUM Cardiovascular, USA), and CADScor System™ (Acarix AB, Sweden). In experimental studies, these test systems showed statistically significant detection of obstructive coronary artery lesions with a sensitivity of 81%–89.5% and specificity of 53%–83% [16].

In general, electronic stethoscope use expands auscultation capabilities by enhancing sound amplification and suppressing background noise.

DOI: https://doi.org/10.17816/DD632499

Digital Stethoscope

The vast majority of modern electronic stethoscopes are equipped with a function to record and transmit sound to a computer or smartphone. By instructing the patient on how to position the stethoscope head, the physician can remotely auscultate and analyze the sounds. This enables remote monitoring of patients under quarantine (e.g., due to COVID-19) or in hard-to-reach areas, as well as the simultaneous interpretation of auscultatory sounds by multiple specialists to improve the quality of telemedicine consultations [17].

Another advantage of the digitalization of auscultation is the improved quality of medical student training. Auscultation simulators reproduce pre-recorded sounds from patients with various heart and lung diseases, allowing an entire audience to listen to the same recording [18]. The ability to display signals graphically as a spectrogram makes auscultation training more visual and facilitates the identification of spectrographic “patterns” associated with specific diseases [19].

The digitization of data has also enabled the use of artificial intelligence (AI) algorithms for sound analysis, opening new possibilities for auscultation. The most common method for sound processing is the Fourier transform, which analyzes the frequency components of the signal. A machine learning algorithm based on an artificial neural network can further process obtained information and correlate different frequencies with specific auscultatory findings. Gurung et al. [20] conducted a meta-analysis of studies to assess the predictive potential of combining digital lung auscultation with computational data analysis algorithms. The sensitivity and specificity of detecting pathological lung sounds using computational algorithms were 85% and 80%, respectively.

The next step in the development of digital auscultation was the ability not only to detect pathological sounds produced by internal organs, but also to diagnose diseases using computational algorithms. For example, Kaddoura et al. [21] analyzed the potential for diagnosing pulmonary hypertension based on heart and lung auscultation. Auscultatory findings obtained with a digital stethoscope were compared between healthy individuals and patients with pulmonary hypertension. The computer algorithm diagnosed pulmonary hypertension based on auscultation data in 74% of cases.

Thus, the modern digital stethoscope offers the following advantages [22]:

High-quality sound signals. Amplification of sounds produced by internal organs and ambient noise suppression facilitate auscultation in high-noise environments, such as in the field, in emergency zones, overcrowded hospital wards, and during patient transportation.

Remote patient examination. The absence of direct contact is essential when patients are geographically remote or when clinicians must use personal protective equipment under radiation, biological, or chemical hazard conditions.

Monitoring of acoustic phenomena in outpatient settings. Continuous auscultation during rest and daily activities, including physical exertion, as well as data collection from multiple sensors placed on different body regions, enable over-time patient assessment.

Auscultation data storage. The ability to reassess recorded data improves the effectiveness of telemedicine consultations and supports resolution of disputes in forensic practice. A database of auscultatory recordings typical of various diseases can be used in the training of medical students.

Disease diagnosis using AI algorithms.

A comparison between traditional and electronic stethoscopes is presented in Table 1.

All digital stethoscope models currently available on the market are equipped with sound amplification and noise reduction functions, as well as the ability to record and transmit acquired data to a personal computer or smartphone via Bluetooth. The 3M™ Littmann® 3200 stethoscope (3M Littmann, USA) is one of the most widely used tools for digital auscultation (Fig. 1*a*). This device amplifies the sound signal 24-fold and features two auscultation modes (for low- and high-frequency sounds). A backlit liquid crystal display shows heart rate (HR), auscultation mode, volume level, and battery status. The device records data in 30-second tracks, which are saved as audio files. The recorded sounds can be visualized as phonocardiograms using StethAssist™ software [23]. Digital stethoscopes manufactured by 3M™ are the most commonly used tools for evaluating the advantages of digital

Table 1. Comparative characteristics of traditional and electronic stethoscopes

Feature	Traditional stethoscope	Electronic stethoscope
Sound amplification	No	Yes
Noise reduction	No	Yes
Versatility for auscultation of internal organs	Yes	Not all models
Data recording and transmission	No	Yes
Use of AI algorithms	No	Yes
Dependence on power supply	No	Yes
Cost of the device and replaceable parts	Low	High

Note. AI, artificial intelligence.

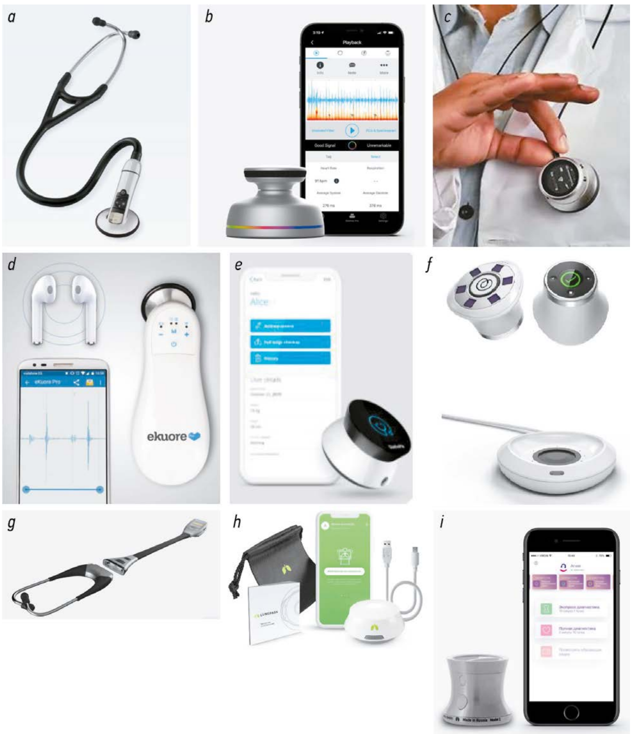

Fig. 1. Appearance of the most popular electronic stethoscopes currently on the market: *a*, 3M™ Littmann 3200 stethoscope (USA), http://stetoskopy.ru/shop/3m-littmann/3200_BK_27.html; *b*, M3DICINE Stethee Pro™ stethoscope (Australia), https://m3dicine.com/#deeper_level; *c*, Thinklabs One™ stethoscope (USA), https://www.thinklabs.com/stethoscopes; *d*, eKuore Pro™ cardiology stethoscope (Spain), https://www.deal-med.ru/stetoskop_elektronniy_ekuore_pro.html; *e*, StethoMe™ stethoscope (Poland), https://www.stethome.com/en-gb/; *f*, Sensors of the CADence™ system for cardiac disease diagnostics (USA), https://evercare.ru/cadence; *g*, Ekoscope™ stethoscope with ECG recording capability (USA), https://ekoscope.com/ekoscope; *h*, Healthy Networks Lung Passport™ stethoscope (Belarus), https://cetez.ru/lungpass/; *i*, Laeneco™ stethoscope (Russia), https://laenecocom.tmweb.ru/.

auscultation [24]. The Stethee Pro™ stethoscope (M3DICINE, Australia) amplifies sound 24-fold during direct auscultation and 96-fold when used with the Stethee Pro™ application. It captures and analyzes sounds in the frequency range from 20 Hz to 2 kHz, followed by AI-based interpretation using the AIDA™ algorithm (Fig. 1*b*). Like the previous device, it features the ability to visualize sound as a phonocardiogram on the screen of the receiving device. It is also equipped with a lithium battery with fast USB charging. Another advantage is the compact size of the model [25].

The most compact and lightweight digital stethoscope on the market with the highest sound amplification (up to 100-fold) is the Thinklabs One™ (Thinklabs, USA) (Fig. 1*c*). It supports multiple auscultation modes and features customizable noise filtering with the option to disable it entirely. This stethoscope allows clinicians to examine patients using personal protective equipment, such as in infectious disease units treating COVID-19 patients, and integrates with most videoconferencing and telemedicine systems [12]. The eKuore Pro™ stethoscope (eKuore, Spain) is another device suitable for both in-person and remote auscultation (Fig. 1*d*). The device analyzes data using AI and easily integrates with any computer or smartphone software. Its distinctive features include the ability to replace the part that contacts the patient's body and data transmission via Wi-Fi [26]. The StethoMe™ stethoscope (StethoMe, Poland) is designed for home care services and patient self-monitoring in cases of cardiac and respiratory diseases, such as bronchial asthma (Fig. 1*e*). This stethoscope detects pathological breath sounds using the StethoMe AI™ system and automatically transmits the data to a physician, enabling remote monitoring of disease changes in the patient. A unique feature of this stethoscope is its capability to measure body temperature [27]. The CADence™ diagnostic system (AUM Cardiovascular, USA) combines a stethoscope and an electrocardiograph, with built-in sensors for recording electrocardiogram data (Fig. 1*f*). This system operates with the CADence Software™ application for clinical decision support, which assists clinicians in analyzing auscultatory findings in combination with ECG results. Data collection takes approximately 8 minutes, after which a report is automatically sent via email within 12 minutes [28]. The Ekoscope™ device (Ekoscope, USA) is another multifunctional medical tool that enables simultaneous cardiac auscultation and six-lead ECG recording (Fig. 1*g*). It is equipped with a microUSB port for battery charging and data transfer [29]. The Lung Passport™ stethoscope (Healthy Networks, Republic of Belarus) is intended for home-based diagnosis of respiratory diseases (Fig. 1*h*). The device is equipped with a mobile application that uses AI algorithms to analyze the recorded sounds, compares them with those characteristic of pneumonia, chronic obstructive pulmonary disease, bronchial asthma, and several types of bronchitis, and then generates a preliminary diagnosis. To improve diagnostic accuracy, the application also includes a patient questionnaire [30]. The Russian Laeneco™ stethoscope (Laeneco, Russia) is designed for both self-diagnosis and remote physician assessment based on audio recordings (Fig. 1*i*). AI-based data analysis takes 2 minutes, after which the device provides a conclusion regarding the presence or absence of pathological sounds, without issuing a diagnosis [31]. A comparative overview of various digital stethoscope models is presented in Table 2.

Thus, the devices described above offer varying functionalities. Some are suitable for patient self-diagnosis, whereas others are intended exclusively for physician use. Additional features of these stethoscopes—such as ECG recording, sound visualization, and body temperature measurement—are particularly noteworthy. Undoubtedly, a significant limitation of several digital stethoscope models is their specialization in auscultation of either the lungs or the heart only. Another obstacle to the widespread adoption of digital stethoscopes is the relatively high cost of the devices and their replaceable components, as well

Table 2. Comparative characteristics of the most popular digital stethoscope models on the market

Stethoscope model (manufacturer, country)	Advantages	Disadvantages
3M™ Littmann 3200 (Littmann, USA)	• Heart rate (HR) recording • Phonocardiogram visualization • Auscultation of the heart and lungs	• No AI-based data analysis • Not suitable for patient self-diagnosis • Not compatible with PPE use • No rechargeable battery (powered by AA batteries)
Stethee Pro™ (M3DICINE, Australia)	• Respiratory rate, heart rate, systole and diastole duration monitoring • Phonocardiogram visualization • Auscultation of the heart and lungs • Use of AI-based data analysis • Compatible with PPE use • Lithium battery	• Not suitable for patient self-diagnosis
Thinklabs One™ (Thinklabs, USA)	• Auscultation of the heart and lungs • Compatible with PPE use • Lithium battery	• No AI-based data analysis • Not suitable for patient self-diagnosis
eKuore Pro™ (eKuore, Spain)	• Auscultation of the heart and lungs • Compatible with PPE use • Wi-Fi connectivity • Remote monitoring capability • Lithium battery	• No AI-based data analysis • Not suitable for patient self-diagnosis
StethoMe™ (StethoMe, Poland)	• Auscultation of the heart and lungs • Use of AI-based data analysis • Compatible with PPE use • Remote monitoring capability • Suitable for patient self-diagnosis • Body temperature measurement • Lithium battery	• No headphones
CADence™ (CADence, USA)	• ECG recording • Lithium battery	• No lung auscultation • Not suitable for patient self-diagnosis
Ekoscope™ (Ekoscope, USA)	• ECG recording • Use of AI-based data analysis • Lithium battery	• No lung auscultation • Not suitable for patient self-diagnosis • Not compatible with PPE use
Lung Passport™ (Healthy Networks, Belarus)	• Use of AI-based data analysis • Suitable for patient self-diagnosis • Lithium battery	• No heart auscultation
Laeneco™ (Laeneco, Russia)	• Use of AI-based data analysis • Suitable for patient self-diagnosis • Lithium battery	• No heart auscultation

Note. HR, heart rate; AI, artificial intelligence; PPE, personal protective equipment; RR, respiratory rate; ECG, electrocardiogram.

as the complexity and expense of repairs due to the low geographic density of service centers. Nevertheless, the rapid development of clinical decision support systems and AI algorithms, along with the growing need for technologies that enable remote monitoring and telemedicine, position these devices as a promising segment in the medical device industry and market.

Over the past few decades, the development of AI has profoundly transformed key areas of everyday life, including healthcare. It has been shown that healthcare digitalization improves the quality of medical care, enhances treatment adherence, and enables early detection of diseases or their exacerbations [32]. The use of a digital stethoscope allows auscultation findings to be recorded and stored, thereby eliminating subjectivity in data interpretation. Market analysis indicates that an increasing number of medical devices are patient-centered, enabling self-diagnosis at home. Digital stethoscopes are no exception: home-use digital stethoscopes equipped with AI-based diagnostic algorithms represent a distinct market niche. Furthermore, the use of such devices by patients in outpatient settings may help reduce the burden on primary healthcare services. For instance, preliminary assessments suggest that the use of the Lung Passport device may reduce the number of doctor visits by 35% [7]. Remote patient monitoring and examination using personal protective equipment contributes to reducing contact between the patient and the healthcare professional, making the examination process as comfortable as possible for both parties. The use of fast-charging, high-capacity batteries and additional functions (ECG and thermometry) may further enhance the competitive advantages of these devices.

CONCLUSION

Enhancing the functionality and versatility of digital stethoscopes (including the ability to analyze sounds from the heart, lungs, intestines, and other organs) as well as improving noise reduction and signal filtering, make these devices increasingly attractive for clinical use. As these challenges are addressed, the digital stethoscope is set to become an indispensable tool for the diagnosis, monitoring, and treatment of diseases, as well as for patient self-monitoring. A particularly promising area of application for modern digital stethoscope models is telemonitoring of patients with cardiovascular and respiratory diseases. Of particular importance is the changes assessment of auscultatory findings over time, which may enable the early detection of complications and decompensation in various chronic non-infectious diseases, such as chronic obstructive pulmonary disease, bronchial asthma, myocardial infarction, and others.

ADDITIONAL INFORMATION

Funding source. This article was not supported by any external sources of funding.

Competing interests. The authors declare that they have no competing interests.

Authors' contribution. All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work. A.A. Garanin — literature review, collection and analysis of literary sources, writing the text and editing the article, final approval for publication; O.Yu. Aydumova — literature review, collection and analysis of literary sources, preparation and writing the text of the article; A.O. Rubanenko — collection and analysis of literary sources, writing and of the text and editing the article; E.G. Bibikova — literature review, collection and analysis of literary sources and writing the text of the article.

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