Introduction

At the current stage of the evolution of society, changes induced by the integration of digital technologies into different areas of human activity have been seen not only in industries making use of high-tech equipment, but also in industries traditionally regarded as less subject to the application of technology because of their nature, as well as in the arts, the humanitarian sciences, education, and medicine. Digitization is now a key vector in the development of industry and the cause and source of changes affecting the processes or aspects of one or another area of human life and activity. Apart from national trends determining the direction of the development of industries in particular countries and defining their national cultural specifics, state policy and the level of development of science and technology, there are also global trends of an interindustry and/or supranational nature. One such trend is the exploitation of the potential of high-tech solutions and knowledge-intensive technologies to increase the quality of medical services and their personalization [1]. The use of digital technologies in healthcare is the basis of the development of medicine and the growth of the market for medical products and services in the 21st century. Digitization in healthcare is a current direction in its development. It increases the effectiveness of existing diagnostic and therapeutic methods and leads to the development of new medical IT solutions and the establishment of personalized and predictive (prognostic) approaches in medicine. This article considers the main directions in the digitization of the healthcare industry and the potential for its development using end-to-end technologies.

Main Directions in the Digitization of Medicine

Many advanced medical technologies are associated with the use of software and instruments based on state-of-the-art digital industrial and end-to-end technologies (Fig. 1). The greatest potential for digital technologies at the present time is in the fields of cloud services, Big Data, digital platforms, the internet of things, artificial intelligence, and industrial and service robots.

The use of digital technologies in medicine can be regarded as occurring at two interrelated levels: provision of medical services and the development of new methods and means.

The digital transformation is most obvious at the level of medical service provision, as it alters the nature of the interaction between doctor and patient. Telemedicine is ever more widely practiced. The use of Big Data technologies to acquire and process information on patients and blockchain technologies for the reliable storage and rapid access to this information decrease the time taken for investigation and diagnosis, provide more accurate reports on changes in a person’s state of health using devices based on the internet of things technology, along with information from the various medical organizations attended by the patient for observation or treatment. Inte-
Integration of digital technologies increases quantitative indicators (decreases in the time and cost of investigations and treatment of patients) as well as qualitative indicators (increased diagnostic accuracy and treatment efficacy). Digitization includes the use of software and technical solutions such as biomedical (MRI systems, etc.) and analytical (amplifiers for DNA analysis of every type, DNA and protein sequencers, biological polymer synthesizers, mass spectrometers, electron microscopes, etc.) equipment for diagnosis and treatment.

The penetration of digital technologies into the development of medical devices, medicines, and treatment methods and means allow the effectiveness of these processes to be increased and their resource intensity to be decreased. Medicine is a domain with very strict ethical norms so the ability to carry out trials and approve medical solutions using computer modeling and virtual simulations is of great importance. These methods allow certain drawbacks to be eliminated before the clinical trial stage. Digital modeling of medical devices and instruments decreases their development and production costs by producing more accurate working characteristics and running virtual trials on computer models. Processing and analysis of large datasets obtained using contemporary devices allows relationships between different parameters to be established and more accurate data to be obtained on disease characteristics and course of illness, and the physiological and genetic features of a patient to be considered when assigning treatment. This is a step on the path to personalized medicine. Processing of large datasets using artificial intelligence systems allows medical trial data to be analyzed and promising directions in scientific research to be identified.

Medical Application of Digital Technologies: Current State and Trends

A dynamically developing direction in digitization of healthcare is telemedicine — remote provision of medical services such as primary diagnosis and complex health monitoring of patients, consultations, self-diagnosis and self-management using special online services and apps [3]. The demand for telemedicine services is high and continues to grow (Fig. 2). New directions in telemedicine are associated with the organizational aspect. These include medical marketplaces (aggregators) and telemedicine service provider platforms operating between patients and doctors: 24/7 Pediatrician (Russia), Doctor Smart (Russia), Health Mail.ru (Russia), and Online Doctor (Russia), as well as online clinics offering medical services exclusively in the telemedicine format: Yandex Health (Russia) and Doc+ (Russia) [4].

Telemedicine requires the development and introduction of specialized platforms for collecting information and combining the information systems of different medical institutions into a single network [6]. The functions of these platforms or networks are to collect, store, host, and transfer people’s personal information between information systems. It is therefore critically important to ensure data and document protection. This task can be solved using blockchain technology. A variety of blockchain projects, both under development and already in operation, provide evidence that IT solutions based on this technology are in demand in the field of healthcare and are indeed needed [7, 8]. Medical IT solutions based on blockchains are used in clinical trials [6], in organizations involved in medical document storage and control.
Development of Digital Technologies in Medicine

The main area of use of this technology in medicine is currently in the field of electronic health cards (EHC). EHC storage systems developed on the basis of blockchain technology (Medicalchain, UK; BurstIQ, USA; and others) provide for the secure storage and authorized access to current data on patients with their consent. Blockchain technologies make the risk of deliberate distortion or destruction of EHC data minimal. Additional capabilities of EHC are provided by smart contracts (Robomed Network, Russia) and smart card users (Guardtime, Switzerland), which record every cardholder’s attendance at a medical institution [12, 13]. The EHC gives the doctor full access to the necessary information in patient’s medical cards and data from medical devices, and to the results of analyses of genomic, pharmacogenomic, exposome, anatomical, and other patient data (DeepMind Technologies, USA; Doc.ai, USA) [7]. Along with providing medical services, Blockchain projects use new technologies promoting predictive medicine (Doctor Smart, Russia; Bioritmai, Belarus) [12] or are focused on creating secure clinical data repositories suitable for medical trials (Ze-nome Blockchain, Belize; Arna Panacea, Russia) [6] are important for scientific and practical applications.

Telemedicine involves not only consulting, but also the whole spectrum of medical services capable of remote delivery. This is possible because of the development of medical robot technologies, including diagnostic and rehabilitation systems, surgical and therapeutic robots, remote history, etc. Apart from telemedicine, medical robot technology is used to obtain qualitatively novel solutions in prosthetization, rehabilitation of patients, and care for them, laboratory investigations, and staff training.

The most effective achievement in telemedicine is robot-assisted surgery — the integrative application of advances in robot technology with mixed reality and the internet of things for carrying out surgery. One of the first such operations was coronary surgery performed by specialists at the Ahmedabad Institute of the Heart (India) in 2019 [14] and, in Russia, surgery to remove the renal artery at the Almazov National Medical Research Centre (St. Petersburg) in 2019 [15]. Remote-controlled robotic surgical systems have been used in hundreds of thousands of surgical procedures [16]. Robotic surgical systems have been developed by large companies and startups such as Renishaw (UK), EndoControls (France), Era Endoscopy (Italy), Rehab-Robotics (Hong Kong), Olympus (Japan), Neurobotics (Russia), Mazor Robotics (Israel), KUKA (Germany), Elekta (Sweden), and Intuitive Surgical (USA). A robotic surgical system usually includes a control unit for the operating surgeon (console and monitor) and an executive unit, including manipulators and instruments, different systems having different numbers of these. Use of medical robots in surgical operations increases the quality and safety of procedures, thereby reducing post-operative rehabilitation time for patients [16].

Medical robots are used to carry out routine procedures related to cleaning facilities, carrying out basic investigations, sorting samples and running laboratory tests on them, and controlling long-term treatments of human body parts or treatments requiring high-precision control of medical instruments. Use of robots to carry out procedures that might have an adverse effect on health
of medical staff (for example, X-rays or working with patients in quarantine) reduces the risk of illness in medical staff, minimizing contact with patients and thus, ensuring effective care [6]. The abilities of robot technology are explored in the manufacture of bionic prostheses and means of making mechanotherapy robots (exoskeletons, exohands, etc.), which are used in the rehabilitation of patients to restore impaired and compensate for lost musculoskeletal functions [13]. Medical robots can be used for educational purposes as trainers. For example, Eidom medical stimulators (Russia) are used in training students and staff to develop skills in providing urgent care and resuscitation.

Integration of digital technologies into medical practice and the healthcare sector is significantly dependent on the ability to obtain data from medical devices and control them remotely and on their ability to function autonomously and interact with each other. These possibilities are supported by the use of the internet of medical things (IoMT) technology, which refers to the concept of a computational network of medical devices, sensors, and equipment interacting with each other and with the external environment via data transmission protocols with the purpose of influencing prophylactic, therapeutic, and rehabilitation processes [17].

IoMT devices can be divided into four main categories: diagnostic, prophylactic, therapeutic, and rehabilitation. The first group includes devices such as digital tonometers, urine analyzers, ultrasound devices, glucometers, thermometers, and urine flowmeters. The second category includes nonspecialized gadgets with medical functions, such as fitness trackers, pulse-meters, scales determining fat content, heart sensors, devices determining the calorie content and detecting harmful substances in food products, etc. Devices used for therapeutic purposes such as insulin pumps or smart “pillboxes” can be placed in a separate category. The last group consists of devices able to help in the rehabilitation of a patient and increase his/her quality of life after surgery or disease. Diagnostic sensors have attracted the greatest level of practical application for patient health monitoring and treatment. There are such examples as the heart sensor from EarlySense (Israel), the wearable Sensor Dot device (Byteflies, Belgium/USA) for predicting epileptic attacks, internally delivered C-Scan sensors (Check-Cap, Israel) to obtain computer images, Proteus Discover patches bearing sensors attached to the patient’s body and used with absorbable sensors (Proteus Digital Health, USA) to collect patient data, etc. [18]. IoMT systems allow digital clinics to be created, producing digital transformation of some of the processes occurring within them, such as monitoring equipment operation, allocating patients to available locations (AutoBed from GE Healthcare, USA), providing access to patients’ electronic record cards, etc. [13].

Medicine is a field of activity requiring the acquisition and processing of large volumes of data: patient investigation results; reports on chronic, inherited, and previous diseases and treatment methods; reports coming from domestic medical devices and nonspecialized gadgets; etc. A significant quantity of information comes from medical robotic devices during their use. The employment of medical solutions based on Big Data technology provides for more accurate and faster diagnosis and implementation of the principles of predictive medicine: prediction of diseases and complications for their prevention and prompt treatment [19]. Even more information needs to be collected and analyzed to support efficient and coordinated operation of medical organizations and to determine national policies in the field of healthcare. At the level of the administration of individual organizations (clinics, polyclinics), Big Data technology identifies factors and barriers to the growth of the effectiveness of administration on the basis of analysis of the characteristics of staff functioning, equipment and systems workload, as well as the consumption of materials and medicines [20]. At the level of national healthcare systems, Big Data technology provides the opportunity to evaluate the efficiency of systems overall for an entire country or its regions, tracking the movement of budget and non-budget resources, predicting the propagation of epidemics and pandemics, and analyzing measures to prevent and delay them [21]. At the level of medical science, Big Data technology is used to solve descriptive, diagnostic, and predictive analytical tasks at different levels of complexity, including processing of data with unclear or nontrivial interactions [22]. The use of bioinformatics methods provides for analysis and interpretation of large experimental databases, as well as studies of genomic data to solve clinical tasks associated with diagnosis and the search for methods of treating oncological, genetic, and infectious diseases [23, 24]. Big Data and bioinformatics are linked with the use of artificial intelligence to process data and test algorithms.

Systems based on artificial intelligence (AI) allow patterns in large datasets to be recognized and established, with formation of predictive models [6]; these are used to solve diagnostic tasks and to address the prognosis of oncological and cardiac diseases (Watson Health, IBM, USA; Botkin.AI, Intellogic, Russia), ophthalmological diseases (Deep Mind Health, Google Health, USA), fetal developmental pathology (ScanNav, MedaPhor, UK), the diagnosis of infectious diseases by microimaging of blood preparations (BIDMC, Israel), and others [25]. Another direction in the use of AI in medicine consists of drug design - the development, study, and improvement of
drugs, therapeutically significant substances, and biologically active molecules employing the methods of computational chemistry, bioinformatics, digital modeling, and algorithmic design methods [6]. Drug design is based on the iterative construction of neuron active molecule with a stable structure and specified properties and includes a variety of methods using search and evolution algorithms. The first successful example of the use of drug design was the carbonic anhydrase inhibitor dorzolamide, which was approved for use in 1995. Another example was the creation of imatinib, a tyrosine kinase inhibitor developed to block the fusion protein bcr-abl. In the pandemic, digital drug design techniques were first used during COVID-19.

Conclusions

The digital transformation of medicine is linked with the end-to-end introduction of digital technologies into this industry at different organizational levels. It opens up wide perspectives not only for increasing the quality of the delivery of healthcare to the patient, but also for the creation of new high-tech devices and equipment, the development of methods, means, and approaches for treatment, and administrative and control processes in the healthcare sector with the aim of improving them.

Telemedicine, medical robotics, the internet of medical things, bioinformatics, medical IT solutions based on big data technologies, artificial intelligence, the blockchain, etc. are changing this industry both at the instrumental level and at the level of establishing novel approaches to healthcare: personalized and predictive medicine.

The COVID-19 pandemic gave an additional impulse to the digitization of medicine, where contemporary IT solutions are used for the analysis, prediction, and reduction of morbidity, as well as for developing means of treating patients and caring for them. At the same time, it should be noted that achievements in digital medicine do not alter the industry’s need for highly qualified specialists and are most effective when patients are participatory, i.e., when they are involved in the processes of maintaining their own health.

REFERENCES

1. The Development of Individual High-Tech Fields: A White Book [in Russian], M. Yu. Sokolov and L. D. Eidel’kind (eds.), NIU VShE, Moscow (2022).
2. Digital Economics: A Short Statistical Collection [in Russian], G. I. Abdarkhananova, S. A. Vasil’kovskii, K. O. Vishnevs’kii, et al. (eds.), NIU VShE, Moscow (2022).
3. Buranbaeva, L. Z., Zhilina, E. V., and Abramov, N. R., “Telemedicine as a direction in the development of the digital technologies market in healthcare,” Vestnik BIST, No. 3 (52), 75-80 (2021).
4. Khodyryeva, L. A., Gritskov, I. O., Vasil’ev, A. O., and Pushkar’, D. Yu., “Telemedicine: current capacities and prospects for further development,” Moskov. Med., No. 3 (43), 90-96 (2021).
5. The Digital Maturity of Healthcare; https://issek.hse.ru/news/385932985.html (accessed February 17, 2022).
6. Biomedical Informatics Computer Applications in Health Care and Biomedicine, E. H. Shortliffe and J. J. Cimino (eds.), Springer, Champaign (2021).
7. Litvin, A. A., Korenev, S. V., Knyazeva, E. G., and Litvin, V. A., “The possibilities of blockchain technology in medicine,” Sovrem. Tekhnol. Med., 11, No. 4, 191-199 (2019).
8. Kuo, T. T., Kim, H. E., and Ohno-Machado, L., “Blockchain distributed ledger technologies for biomedical and health care applications,” J. Am. Inform. Assoc., 24, No. 6, 1211-1220 (2017).
9. Dokukina, I. A., “Characteristics of the formation of a decentralized data control system in medical institutions based on blockchain technology,” Vestn. TGU Ser. Ekon. Uprav., No. 3, 106-112 (2018).
10. Kozenko, Yu. A. and Kozenko, T. E., “Routing manage- ments of the therapeutic process using blockchain technologies,” Sib. Finans. Shkola, No. 3 (134), 25-27 (2019).
11. Koshechkin, K. A., Preferanskii, N. G., and Preferanskaya, N. G., “Use of blockchain technologies for management of a drug register,” Vrach Informats. Tekhnol., No. 3, 58-64 (2019).
12. Yoon, H. J., “Blockchain technology and healthcare,” Healthc. Inform. Res., 25, (2), 59-60 (2019).
13. Vyas, S. and Bhargava, D., Smart Health Systems: Emerging Trends, Springer, Singapore (2021).
14. Patel, T. M., Shah, S. C., and Pancholy, S. B., “Long distance tele-robotic-assisted percutaneous coronary intervention: A report of first-in-human experience,” EClinicalMedicine, 14, 53-58 (2019).
15. DAVINCI. Robotic Surgery in Russia, https://robot-davincki.ru (accessed February 17, 2022).
16. Turkina, N. V., “Robot-assisted operations,” Meditsinsk. Sestra, No. 6, 11-14 (2017).
17. Lebedev, G. S., Shaderkin, I. A., Fomina, I. V., Lisnenko, A. A., Ryabok, I. V., Kachkovskii, S. V., and Melaev, D. V., “The internet of medical things: first steps in systematization,” Ross. Zh. Telemed. Elektron. Zdravoookhr., No. 3, 128-136 (2017).
18. Zinyakova, E. V., “The internet of things as the basis of high-tech medicine,” Sinergiya Nauk, No. 43, 454-459 (2020).
19. Zhao, J., “The application and influence of big data in medicine,” in: BIC 2021: Proceedings of the 2021 International Conference on Bioinformatics and Intelligent Computing, Harbin, January 22-24, 2021, ACM, New York (2021), pp. 1-5.
20. Karnaukhnov, N. S. and Il’yukhin, R. G., “The capacities of ‘Big Data’ technologies in medicine,” Vrach. Informats. Tekhnol., No. 1, 58-53 (2019).
21. Sabarish, J., Sonali, S., and Vidhya, P. T. R., “Application of big data in field of medicine,” Adv. Intell. Syst. Comput., 1167, 473-484 (2021).
22. Schaefer, G. O., Tai, E. S., and Sun, S., “Precision medicine and big data,” Asian Bioethics Rev., 11, No. 6, 275-288 (2019).
23. Ott, P. A., Hu, Z., and Keskin, D. B., “An immunogenic personal neoantigen vaccine for patients with melanoma,” Nature, 547, 217-221 (2017).
24. Bioinformatics: Methods and Applications, D. B. Singh and R. K. Pathak (eds.), Academic Press, India (2022).
25. Kendale, S., Kulkarni, P., Rosenberg, A. D., and Wang, J., “Supervised machine-learning predictive analytics for prediction of postinduction hypotension,” Anesthesiology, 129, No. 4, 675-688 (2018).