

Читать
онлайн
Read
online

Dimitra I. Nikolopoulou¹, Thomas Karampatzakis², Demetrios Kouretas²,
Dmitry S. Fedorov³, Antonis Tsintarakis⁴, Evangelos Kirithras¹,
Ali Taghizadehghalehjoughi⁵, Valerii N. Rakitskii⁶

Nanorobotics in biomedical sciences (literature review)

¹Medical School, University of Crete, Heraklion, 71003, The Hellenic Republic;

²University of Thessaly, Larissa, 41500, The Hellenic Republic;

³Siberian Federal Scientific Centre of Agro-BioTechnologies of the Russian Academy of Sciences, Krasnoobsk, 630501, Russian Federation;

⁴Institute of Chemical Biology, National Hellenic Research Foundation, Athens, 11635, The Hellenic Republic;

⁵Bilecik Sheikh Edebalı University, Bilecik, 11230, The Republic of Turkey;

⁶Federal Scientific Center of Hygiene named after F.F. Erisman, Mytishchi, 141014, Russian Federation

ABSTRACT

Nanomedicine is a scientific field resulting from the combination of nanotechnology and medicine, utilizing the high accuracy and wide adaptability of functional nanoscale devices called nanorobots or nanobots. Nanobots are emerging as key players in novel medical applications and, in conjunction with the rapidly evolving Artificial Intelligence (AI) technologies, may significantly improve the treatment and diagnostic outcomes in the context of precision medicine. Nanorobotics, as a subfield of nanomedicine, involves the design, creation, and deployment of autonomous or semi-autonomous nanoscale devices capable of performing specific medical tasks at the molecular or cellular level. The integration of AI further enhances the capabilities of nanobots by enabling them to adapt to dynamic biological environments, learn from interactions, and optimize treatment strategies. Their precision and ability to operate at the cellular or subcellular scale are particularly advantageous in targeting diseases at their source, such as cancer or genetic disorders, without causing damage to surrounding intact tissues. Herein, this short review article aims to present an overview of the most conventional nanobot-based therapeutics and diagnostics that have been widely explored so far. Furthermore, we emphasize on the challenges this technology faces in clinical application, detailing issues in safety assessment, diverse biological effects, and regulatory restrictions. Finally, we provide our perspective on the future directions of nanomedicine.

Keywords: nanobots; nanotechnology; artificial intelligence; biomedicine; review

For citation: Nikolopoulou D.I., Karampatzakis Th., Kouretas D., Fedorov D.S., Tsintarakis A., Kirithras E., Taghizadehghalehjoughi A., Rakitskii V.N. Nanorobotics in biomedical sciences (literature review). *Gigiena i Sanitariya / Hygiene and Sanitation, Russian journal*. 2025; 104(9): 1204–1208. <https://doi.org/10.47470/0016-9900-2025-104-9-1204-1208> <https://elibrary.ru/aynxcp>

For correspondence: Dmitry S. Fedorov, e-mail: dmtry.fedorov@gmail.com

Contribution: Nikolopoulou D.I. — writing text, the concept and design of the study, editing; Karampatzakis T. — writing text, the design of the study, editing; Kouretas D. — writing text, editing; Fedorov D.S. — writing text, editing; Tsintarakis A. — writing text, editing; Kirithras E. — editing; Taghizadehghalehjoughi A. — editing; Rakitsky V.N. — editing. All authors are responsible for the integrity of all parts of the manuscript and approval of the manuscript final version.

Conflict of interest. The authors declare no conflict of interest.

Funding. The study had no sponsorship.

Received: April 15, 2025 / Accepted: June 26, 2025 / Published: October 20, 2025

Николопулу Д.И.¹, Карампатзакис Т.², Куретас Д.², Федоров Д.С.³, Цинтаракис А.⁴,
Киристрас Е.¹, Тагизадегхалехджоуи А.⁵, Ракитский В.Н.⁶

Применение нанороботов в биомедицинских науках (обзор литературы)

¹Университет Крита, Ираклион, 71003, Греческая Республика;

²Университет Фессалии, Лариса, 41500, Греческая Республика;

³Сибирский федеральный научный центр агробиотехнологий Российской академии наук, 630501, р.п. Краснообск, Россия;

⁴Институт химической биологии, Национальный фонд исследований Греции (NHRF), 11635, Афины, Греческая Республика;

⁵Университет Биледжик Шейх Эдебали, 11230, Биледжик, Турецкая Республика;

⁶ФБУН «Федеральный научный центр гигиены имени Ф.Ф. Эрисмана» Роспотребнадзора, 141014, Мытищи, Россия

РЕЗЮМЕ

Наномедицина — это научная область, возникшая в результате объединения нанотехнологий и медицины, использующая высокую точность и широкие возможности адаптации функциональных наноразмерных устройств, называемых нанороботами или наноботами. Нанороботы становятся ключевыми элементами в новых медицинских приложениях и в сочетании с быстро развивающимися технологиями искусственного интеллекта (ИИ) могут значительно улучшить результаты лечения и диагностики в контексте точной медицины. Наноробототехника как подобласть наномедицины включает в себя разработку, создание и внедрение автономных или полуавтономных наноразмерных устройств, способных выполнять конкретные медицинские задачи на молекулярном или клеточном уровне. Интеграция искусственного интеллекта ещё больше расширяет возможности нанороботов, позволяя им адаптироваться к динамичной биологической среде, учиться на основе взаимодействия и оптимизировать стратегии лечения. Их точность и способность действовать на клеточном или субклеточном уровне особенно выгодны для борьбы с болезнями в их источнике, такими как рак или генетические нарушения, не причиняя вреда окружающим здоровым тканям. В этой небольшой обзорной статье рассматриваются наиболее традиционные методы лечения и диагностики на основе нанороботов, которые были широко изучены на сегодняшний день.

день. Кроме того, мы акцентируем внимание на проблемах, с которыми сталкивается данная технология при клиническом применении, подробно рассматривая вопросы оценки безопасности, разнообразных биологических эффектов и нормативных ограничений. Наконец, мы представляем наш взгляд на будущие направления развития наномедицины.

Ключевые слова: нанороботы; нанотехнологии; искусственный интеллект; биомедицина

Для цитирования: Николопулу Д.И., Карампатзакис Т., Куретас Д., Федоров Д.С., Цинтаракис А., Киритрас Е., Тагизадегалежджоуи А., Ракитский В.Н. Применение нанороботов в биомедицинских науках (обзор литературы). *Гигиена и санитария*. 2025; 104(9): 1204–1208. <https://doi.org/10.47470/0016-9900-2025-104-9-1204-1208> <https://elibrary.ru/aynxcx>

Для корреспонденции: Федоров Дмитрий Сергеевич, e-mail: dmtry.fedorov@gmail.com

Участие авторов: Николопулу Д.И. — написание текста, концепция и план исследования, редактирование; Карампатзакис Т. — написание текста, концепция и план исследования, редактирование; Куретас Д. — написание текста, редактирование; Федоров Д.С. — написание текста, редактирование; Цинтаракис А. — написание текста, редактирование; Киритрас Е. — редактирование; Тагизадегалежджоуи А. — редактирование; Ракитский В.Н. — редактирование. Все соавторы — утверждение окончательного варианта статьи, ответственность за целостность всех её частей.

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов в связи с публикацией данной статьи.

Финансирование. Исследование не имело финансовой поддержки.

Поступила: 15.04.2025 / Принята к печати: 26.06.2025 / Опубликовано: 20.10.2025

Introduction

Nanotechnology is an interdisciplinary field of science, encompassing fields such as medicine, electronics, and materials science, with a focus on the utilization of particles at the molecular or even atomic level. One of the most prominent applications of nanotechnology is nanorobots (or “nanobots”) programmable nanodevices capable of performing specific tasks at the molecular or cellular level. Currently, nanobots find their implementation in the world of medicine for both diagnostic and therapeutic purposes [1, 2].

Diagnostic and Monitoring capabilities

One of the primary advantages of nanobots is their small size, restricted to a few nanometers in diameter. Due to their size and nano-bioelectronic architecture, nanorobots could be introduced into the bloodstream for real-time *in vivo* health monitoring, emitting electrical signals upon detecting metabolic changes or diseases. Given that they can travel to various, otherwise inaccessible, parts of the body, nanobots have the potential to not only selectively identify metal ions, proteins, and bacterial toxins but also to analyze the blood content. Such utilities offer unlimited possibilities in detecting disease biomarkers and providing accurate pre-treatment analyses [3].

Nanobots' ability to circulate in the vascular system makes them suitable for monitoring blood sugar levels, collecting real-time data that can then be sent to a mobile application installed on a diabetic patient's phone. Furthermore, these nanodevices can be utilized as wireless biopsy or imaging tools, capturing individual cells of interest or collecting tissue samples, with high specificity and selectivity, for the early diagnosis of diseases such as cancer, cardiovascular diseases, and neurological disorders.

In addition to their diagnostic capabilities, nanobots could also be used to monitor a patient's response to treatment. Nanobots may assist healthcare professionals in evaluating the efficacy of a particular therapy and thus making the necessary adjustments by detecting changes in biomarkers over time. Although the development of nanobots for health monitoring and diagnostics is still in infancy, scientists have made great strides in creating these tiny machines. With continued research and development, nanobots have the potential to revolutionize healthcare, resulting in better health outcomes for patients worldwide [4, 5].

Innovative therapeutic applications

Besides their potential utilization as diagnostic tools, nanobots are expected to aid patients suffering from various disorders. One of the most crucial applications lies in their capacity for specialized drug delivery, with the aim of suppressing the development and progression of diseases. Most conventional medications traverse the body, potentially losing some effectiveness, before reaching

the location of interest. The unique features of nanobots can be utilized in order to modulate the permeability of cell membranes to drugs, alter drug solubility and pharmacokinetics, ultimately enhancing their bioavailability. Nanobots can deliver drugs to targeted areas with high precision, significantly improving the effectiveness of therapeutic schemes and diminishing the various potential adverse effects. The applications of nanodevices are practically boundless, encompassing from cancer treatment strategies, innovative tissue engineering techniques, to novel solutions in the field of gene therapies.

Common anticancer drugs often have a limited therapeutic index, with dosages causing toxicity to both healthy and tumor cells. A promising solution lies in nanobots, which can be designed and constructed to specifically respond to disparate cell types [3, 6]. A novel approach involves genetically modified *Salmonella* bacteria that transmit nanodevices with drug-filled capsules, designed for release directly at the tumor site while leaving healthy cells intact [7].

Researchers have developed nanobots by coating gold nanowires with hybrid platelet and red blood cell membranes. This innovative cell membrane coating confers nanobots dual functionalities, that of platelets (binding pathogens like MRSA bacteria, an antibiotic-resistant strain of *Staphylococcus aureus*) and that of red blood cells (absorbing and neutralizing the toxins these bacteria produce). Such proof-of-concept nanobots could, in the future, offer a safe and efficient way to detoxify and decontaminate biological fluids [8].

Another innovative strategy employs RNA-based drugs that can activate telomerase expression in cells. These RNA molecules could be encapsulated in nanobots, forming a nanocage-like structure, and delivered directly to target cells, thereby improving their biodistribution. This allows for precise control over the dosage and timing of telomerase activation. Additionally, nanoparticles capable of delivering small molecules or peptides may also activate telomerase activity. Although the development of telomerase-induced telomere extension via nanobot drug-delivery systems is still in the early stages, it holds great promise for advancing regenerative medicine and potentially extending human lifespan [9].

Targeted delivery of telomerase activators represents an interesting and contemporary approach that combines nanotechnology with drug delivery systems. Specialized nanobots can be programmed for telomere extension in stem cells or tissues particularly susceptible to telomere shortening, and be activated by specific signals, such as inflammation or oxidative stress, to enhance the cells' lifespan. This method could potentially be applied in a variety of chronic age-related diseases, including Alzheimer's or Parkinson's disease, as well as cancer.

Furthermore, nanobots could significantly enhance the treatment of neurodegenerative diseases by providing targeted drug delivery. This could markedly improve therapeutic efficacy, potentially facilitating brain repair by delivering specific neural regeneration agents [10].

Regenerative Medicine and Artificial Organs

With the recent acceleration in biotechnology research, nanobots have shown great potential to transform the field of regenerative medicine by allowing therapeutic agents to be delivered to injured tissues and organs in a more specific and targeted manner. For example, nanobots could stimulate the formation of new tissue, accelerating the healing process by delivering stem cell factors or other growth factors directly to the site of injury [11]. Additionally, nanobots can be designed to mimic the natural extracellular matrix (ECM) of tissues, providing a scaffold for cells to attach and grow [12]. This application is particularly useful for the repair and regeneration of damaged tissues such as bone, cartilage, and muscle.

Another potential application of nanobots in regenerative medicine is the creation of artificial organs. Researchers could potentially manufacture functional tissues and organs for transplantation by utilizing nanobots to recruit and organize cells into more complicated structures [13].

AI integration

Combining AI with nanotechnology results in interesting new concepts in the healthcare industry, including drug delivery, diagnostics, gene therapy, and many other applications that comply with the most innovative tailored therapy approaches of Precision Medicine. AI, the umbrella term for areas of computer science that encompass deep learning, natural language processing, machine learning, and computer vision, can enable machines to replicate human intelligence and perform a variety of complex tasks. Computational intelligence, statistical patterns, object identification, and category prediction can all be achieved using AI algorithms [14]. With the current development of technology, AI could provide a unique opportunity for precision medicine to reach its full potential in the contexts of diagnosis and treatment [15]. AI offers tremendous capabilities for automation, rapid interpretation of complex disease information, and faster processing of composite medical data, dramatically improving treatment outcomes [16].

In recent years, AI tools have been increasingly used for nanotechnology research across various scientific areas, such as scanning probe microscopy, simulations, and nanocomputing. For instance, researchers at Osaka University in Japan discovered that AI can be “trained” to reconstruct high resolution images by processing the brain activity recorded through magnetic resonance imaging (MRI) scans of participants exposed to those specific images [17]. These findings indicate that functional magnetic resonance imaging (fMRI) harbors the potential to “read” people’s minds, raising awareness of the potential misuse of AI capabilities. Another area where AI could be employed involves monitoring the guided delivery of drugs to target organs, tissues or tumors [18].

An important development in AI technologies and nanobots involves their integration into mobile health data collection. The field of mobile health (mHealth) has seen tremendous growth in recent years, with the widespread adoption of smartphones and other mobile devices, providing users with convenient access to health resources [19]. This technology allows for tracking and managing their health and wellbeing in real-time. AI algorithms can mine large amounts of health data to identify patterns and predict future health outcomes. This enables healthcare providers to intervene early, offer personalized recommendations, and even assist in the management of chronic conditions by identifying potential health issues, which can in some cases be lifesaving.

Moreover, a remarkable combination of AI and biology has led to the creation of the world’s first “living robots” [20]. Xenobots, in particular, are created using a combination of computer simulations and genetic engineering techniques to produce cells that are usually “pre-programmed” and often controlled by external stimuli, such as magnetic fields or light, and are capable of self-organization and autonomous navigation. An AI “evolutionary algorithm” was integrated into the computer to

predict animal behavior. Xenobots, like all biobots, are governed by the principles of biomedical engineering, cybernetics, and robotics in order to develop new technologies that integrate biology with mechanical systems. Their design dictates their autonomous functional capacities, which include the ability, in aqua, to move linearly or circularly, swarm, “explore”, push small objects, and hold objects in a “pouch”. They are intended to perform specific tasks, such as acting as transporters in drug-delivery systems, playing an active role in tissue repair, or even detoxifying the circulatory system. Researchers described this invention as “neither a traditional robot nor a known species of animal” but a “new class of artifact: a living, programmable organism” [21].

Challenges and Ethical Considerations

The number of innovations in the field of nanomedicine is increasing, offering new opportunities to improve people’s daily lives. However, novel challenges also arise, necessitating the development of protocols for evaluating the risks. Researchers have not yet fully understood the intricate interactions between nanobots and living systems. The complexity arises from the interactions of the various materials used to build nanobots and the still-unknown health and environmental consequences of nanoparticles [22]. Moreover, the interactions of nanobots with biological matter may change their surface characteristics in a manner dependent on the environment in which they are placed [23–25].

The identification of hazards associated with the use of nanobots in the human body is still in early stages. However, the main challenge is the difficulty to standardize and implement methods that reflect the real toxicity to organs and the routes through which engineered nanomaterials (ENMs) enter the body [26]. Physicochemical properties, such as size, morphology, surface area, and aggregation at larger scales may alter their biodistribution and their interactions with cells and biomolecules, further complicating safety issues. Any changes in the synthetic pathway, reagents, manufacturing method, or route of administration can influence toxicity and thus require a new safety assessment. Once nanomaterials have entered the body, whether as drug delivery or diagnostic tools, they induce physicochemical interactions with the immune system in different tissues [22].

Common cytotoxicity mechanisms of nanomaterials include inflammation, autophagy dysfunction, oxidative stress, cell membrane damage, immune system response, genotoxicity, alteration in cell structural, or cell organelle morphology, and cell cycle arrest [27]. Besides understanding the impact of nanomaterials’ nanotoxicity on the human body, it is crucial to comprehend the molecular mechanisms underlying their toxicity. Alterations in the redox equilibrium within cells, involving produced reactive oxygen species and antioxidants, can lead to chromosomal aberrations, gene mutations, apoptosis, and even carcinogenesis [28]. Furthermore, the inability, with our current understanding, to control the movement of these nanoparticles throughout the body creates a risk, as they could potentially reach undesirable locations and thus lead to unwanted side effects. As previously mentioned, one of the main characteristics of nanoparticles is their ability to cross biological barriers. This could, in some cases, be disadvantageous as it could potentially trigger inflammatory reactions. Acute inflammation is a typical response to an incoming threat, and a nanobot must overcome the host’s immune system clearance to avoid being recognized as foreign material [16], [18].

The intricate nature of the human body poses substantial navigational challenges for nanobots, complicating their effective deployment. Furthermore, fabricating nanobots that are both functional and reliable in significant volumes presents considerable technological barriers. The potential misuse of nanobots for purposes such as biological warfare or unauthorized surveillance adds a layer of ethical complexity [29]. Additionally, the heightened reactivity of nanomaterials could potentially lead to serious health issues, including DNA damage and pulmonary

fibrosis [27]. The integration of AI with nanomedical devices also raises privacy concerns due to the extensive health data they generate [30]. Moreover, the substantial costs of nanomedical technologies could lead to disparities in access to advanced treatments, especially in less developed regions.

The implementation of nanobots into clinical practice faces significant challenges, a primary one being their successful implementation in real-world clinical settings. Critical to their design is the biocompatibility of materials used, ensuring that these nanobots can safely interact within biological environments without adverse effects. Moreover, the choice of energy source for powering nanobots is crucial for their autonomous functioning within the body. Different power sources, such as magnetic, ultrasound, or light-driven propulsion, significantly influence their movement, speed, controllability, and biocompatibility, necessitating careful consideration during the design phase [31].

Despite the accelerated advancement and adoption of new technologies, along with their numerous benefits, it is critical to establish strict, almost rigid, legislative frameworks to ensure the smooth and ethical integration of these innovative biomedical applications into existing health services. It is important to recognize that the regulation and legislation surrounding the use of nanobots, including their application in medical treatments, vary across different regions [32]. The absence of regulation and standards for nanotherapeutics in manufacturing practices, quality control, safety, and efficacy evaluation are a barrier to the development of nanotherapeutics. Currently, there are no global regulatory standards specific to clinical translation of nanotherapeutics. Initial guidance documents for nanotechnology products have only been issued by regulatory authorities such as the Food and Drug Administration (FDA) and the European Medicines Agency (EMA) to provide guidance. In Europe, the use of nanobots in healthcare and related fields is regulated by guidelines that ensure their safety, efficacy, and

ethical use [33]. Current legislation regarding nanobot usage in Europe falls under the broader regulatory framework for medical devices, pharmaceuticals, and nanotechnology. This means the European Medicines Agency (EMA) provides regulatory oversight and evaluation for medicinal products, including nanomedicines, ensuring their quality, safety, and efficacy. Additionally, the European Commission has established the European Union Observatory for Nanomaterials (EUON) to enhance the understanding and awareness of nanomaterials' safety aspects and promote their responsible use. This includes monitoring and evaluating the safety and potential risks associated with nanotechnology applications [34]. Simon Coghlan and Kobi Leins, in their letter to the American Journal of Bioethics, for example, expressed concerns about the greater biological integration of the next biobots, with greater structural complexity and even the possible scenario of the ability to reproduce [35].

Conclusion

There are still many challenges that must be addressed before this technology can be safely implemented and become widely accessible to the general population. These challenges include the evaluation of the biocompatibility and safety of nanobots, the development of a relatively fast and cost-effective way to mass produce nanobots, the establishment of the appropriate legislative context and guidelines that will oversee the development and implementation of such technologies.

It is when humans fail to comprehend machines better than machines comprehend humans that serious risks arise. The very same tools that can be used for our prosperity can also be turned against us. However, if significant advancements are made in AI, engineering and biotechnology, and our understanding of these fields improves, this scenario may change.

Литература / References

1. Anzar N., Yadav N., Narang J. Chapter 21. Nanorobots for improved theranostic applications. In: *Advanced Nanoformulations*. Elsevier; 2023: 587–611. <https://doi.org/10.1016/B978-0-323-85785-7.00002-4>
2. Aggarwal M., Kumar S. The use of nanorobotics in the treatment therapy of cancer and its future aspects: a review. *Cureus*. 2022; 14(9): e29366. <https://doi.org/10.7759/cureus.29366>
3. Kumar S. Nanorobots a future device for diagnosis and treatment. *J. Pharm. Pharm.* 2018; 5(1): 44–9. <https://doi.org/10.15436/2377-1313.18.1815>
4. Zhang Y., Zhang Y., Han Y., Gong X. Micro/nanorobots for medical diagnosis and disease treatment. *Micromachines (Basel)*. 2022; 13(5): 648. <https://doi.org/10.3390/mi13050648>
5. Patra J.K., Das G., Fraceto L.F., Campos E.V.R., Rodriguez-Torres M.D.P., Acosta-Torres L.S., et al. Nano based drug delivery systems: recent developments and future prospects. *J. Nanobiotechnology*. 2018; 16(1): 71. <https://doi.org/10.1186/s12951-018-0392-8>
6. Suhail M., Khan A., Rahim M.A., Naeem A., Fahad M., Badshah S.F., et al. Micro and nanorobot-based drug delivery: an overview. *J. Drug Target*. 2022; 30(4): 349–58. <https://doi.org/10.1080/1061186X.2021.1999962>
7. Jiménez-Jiménez C., Moreno V.M., Vallet-Regí M. Bacteria-assisted transport of nanomaterials to improve drug delivery in cancer therapy. *Nanomaterials (Basel)*. 2022; 12(2): 288. <https://doi.org/10.3390/nano12020288>
8. Esteban-Fernández de Ávila B., Angsantikul P., Ramírez-Herrera D.E., Soto F., Teymourian H., Dehaini D., et al. Hybrid biomembrane-functionalized nanorobots for concurrent removal of pathogenic bacteria and toxins. *Sci. Robot.* 2018; 3(18): eaat0485. <https://doi.org/10.1126/scirobotics.aat0485>
9. Agrahari V., Agrahari V., Chou M.L., Chew C.H., Noll J., Burnouf T. Intelligent micro-/nanorobots as drug and cell carrier devices for biomedical therapeutic advancement: Promising development opportunities and translational challenges. *Biomaterials*. 2020; 260: 120163. <https://doi.org/10.1016/j.biomaterials.2020.120163>
10. Chen B., Tan H., Ding M., Liu L., Wang S., Peng X., et al. Nanorobot-mediated synchronized neuron activation. *ACS Nano*. 2023; 17(14): 13826–39. <https://doi.org/10.1021/acsnano.3c03575>
11. Perán M., García M.A., Lopez-Ruiz E., Jiménez G., Marchal J.A. How can nanotechnology help to repair the body? Advances in cardiac, skin, bone, cartilage and nerve tissue regeneration. *Materials (Basel)*. 2013; 6(4): 1333–59. <https://doi.org/10.3390/ma0041333>
12. Smith I.O., Liu X.H., Smith L.A., Ma P.X. Nanostructured polymer scaffolds for tissue engineering and regenerative medicine. *Wiley Interdiscip. Rev. Nanomed. Nanobiotechnol.* 2009; 1(2): 226–36. <https://doi.org/10.1002/wnan.26>
13. Mitra M. Medical nanobot for cell and tissue repair. *Int. J. Robot. Autom.* 2017; 2(6). <https://doi.org/10.15406/iratj.2017.02.00038>
14. Rani S., Lakhwani K., Kumar S. Three dimensional objects recognition & pattern recognition technique; related challenges: A review. *Multimed. Tools Appl.* 2022; 81: 17303–46. <https://doi.org/10.1007/s11042-022-12412-2>
15. Johnson K.B., Wei W.Q., Weeraratne D., Frisse M.E., Misulis K., Rhee K., et al. Precision medicine, AI, and the future of personalized health care. *Clin. Transl. Sci.* 2021; 14(1): 86–93. <https://doi.org/10.1111/cts.12884>
16. Lee D., Yoon S.N. Application of artificial intelligence-based technologies in the healthcare industry: opportunities and challenges. *Int. J. Environ. Res. Public Health*. 2021; 18(1): 271. <https://doi.org/10.3390/ijerph18010271>
17. Fukuma R., Yanagisawa T., Nishimoto S., Sugano H., Tamura K., Yamamoto S., et al. Voluntary control of semantic neural representations by imagery with conflicting visual stimulation. *Commun. Biol.* 2022; 5: 214. <https://doi.org/10.1038/s42003-022-03137-x>
18. Fukuma R., Yanagisawa T., Nishimoto S., Sugano H., Tamura K., Yamamoto S., et al. Voluntary control of semantic neural representations by imagery with conflicting visual stimulation. *Commun. Biol.* 2022; 5(1): 214. <https://doi.org/10.1038/s42003-022-03137-x>
19. Dicianno B.E., Parmanto B., Fairman A.D., Crytzer T.M., Yu D.X., Pramana G., et al. Perspectives on the evolution of mobile (mHealth) technologies and application to rehabilitation. *Phys. Ther.* 2015; 95(3): 397–405. <https://doi.org/10.2522/ptj.20130534>
20. Coghlan S., Leins K. “Living robots”: ethical questions about xenobots. *Am. J. Bioeth.* 2020; 20(5): W1–3. <https://doi.org/10.1080/15265161.2020.1746102>
21. Arvidsson R., Hansen S.F. Environmental and health risks of nanorobots: an early review. *Environ. Sci. Nano*. 2020; 7(10): 2875–86. <https://doi.org/10.1039/D0EN00570C>
22. Ray P.C., Yu H., Fu P.P. Toxicity and environmental risks of nanomaterials: challenges and future needs. *J. Environ. Sci. Health C Environ. Carcinog. Ecotoxicol. Rev.* 2009; 27(1): 1–35. <https://doi.org/10.1080/10590500802708267>
23. Saptarshi S.R., Duschl A., Lopata A.L. Interaction of nanoparticles with proteins: relation to bio-reactivity of the nanoparticle. *J. Nanobiotechnology*. 2013; 11: 26. <https://doi.org/10.1186/1477-3155-11-26>
24. Yadav R.D., Chaudhary A. Nano-bio surface interactions, cellular internalisation in cancer cells and e-data portals of nanomaterials: A review. *IET Nanobiotechnol.* 2021; 15(6): 519–31. <https://doi.org/10.1049/nbt2.12040>
25. Bhattacharya K., Mukherjee S.P., Gallud A., Burkert S.C., Bistarelli S., Bellucci S., et al. Biological interactions of carbon-based nanomaterials:

- From coronation to degradation. *Nanomedicine*. 2016; 12(2): 333–51. <https://doi.org/10.1016/j.nano.2015.11.011>
26. Albalawi F., Hussein M.Z., Fakurazi S., Masarudin M.J. Engineered nanomaterials: the challenges and opportunities for nanomedicines. *Int. J. Nanomedicine*. 2021; 16: 161–84. <https://doi.org/10.2147/IJN.S288236>
 27. Xuan L., Ju Z., Skonieczna M., Zhou P.K., Huang R. Nanoparticles-induced potential toxicity on human health: Applications, toxicity mechanisms, and evaluation models. *MedComm (2020)*. 2023; 4(4): e327. <https://doi.org/10.1002/mco2.327>
 28. Iqbal M.J., Kabeer A., Abbas Z., Siddiqui H.A., Calina D., Sharifi-Rad J., et al. Interplay of oxidative stress, cellular communication and signaling pathways in cancer. *Cell Commun. Signal*. 2024; 22(1): 7. <https://doi.org/10.1186/s12964-023-01398-5>
 29. Asaro P. Autonomous weapons and the ethics of artificial intelligence. In: Liao S.M., ed. *Ethics of Artificial Intelligence*. New York; 2020. <https://doi.org/10.1093/oso/9780190905033.003.0008>
 30. Rahman M.A., Victoros E., Ernest J., Davis R., Shanjana Y., Islam M.R. Impact of Artificial Intelligence (AI) Technology in healthcare sector: a critical evaluation of both sides of the coin. *Clin. Pathol*. 2024; 17: 2632010X241226887. <https://doi.org/10.1177/2632010X241226887>
 31. Zhou H., Mayorga-Martinez C.C., Pané S., Zhang L., Pumera M. Magnetically driven micro and nanorobots. *Chem. Rev*. 2021; 121(8): 4999–5041. <https://doi.org/10.1021/acs.chemrev.0c01234>
 32. Hua S., de Matos M.B.C., Metselaar J.M., Storm G. Current trends and challenges in the clinical translation of nanoparticulate nanomedicines: pathways for translational development and commercialization. *Front. Pharmacol*. 2018; 9: 790. <https://doi.org/10.3389/fphar.2018.00790>
 33. Malik S., Muhammad K., Waheed Y. Emerging applications of nanotechnology in healthcare and medicine. *Molecules*. 2023; 28(18): 6624. <https://doi.org/10.3390/molecules28186624>
 34. Wasti S., Lee I.H., Kim S., Lee J.H., Kim H. Ethical and legal challenges in nanomedical innovations: a scoping review. *Front. Genet*. 2023; 14: 1163392. <https://doi.org/10.3389/fgene.2023.1163392>
 35. Mühlebach S. Regulatory challenges of nanomedicines and their follow-on versions: A generic or similar approach? *Adv. Drug Deliv. Rev*. 2018; 131: 122–31. <https://doi.org/10.1016/j.addr.2018.06.024>

Information about the authors

Dimitra I. Nikolopoulou, researcher, Laboratory of toxicology and forensic sciences, Medical School, University of Crete, Heraklion, P.O. 71003, The Hellenic Republic, <https://orcid.org/0009-0009-1593-6788> E-mail: d.nikolopoulou@uoc.gr

Thomas Karampatzakis, postgraduate student, Laboratory of animal physiology, Department of biochemistry and biotechnology, University of Thessaly, Larissa, 41500, The Hellenic Republic, <https://orcid.org/0009-0006-9159-9347> E-mail: tkarampatzakis@uth.gr

Demetrios Kouretas, professor, Laboratory of animal physiology, Department of biochemistry and biotechnology, University of Thessaly, Larissa, 41500, The Hellenic Republic, <https://orcid.org/0000-0002-7469-6640> E-mail: dkouret@uth.gr

Dmitry S. Fedorov, junior researcher, Siberian Federal Scientific Centre of Agro-BioTechnologies, Krasnoobsk, 630501, Russian Federation, <https://orcid.org/0000-0001-8678-400X> E-mail: dmtry.fedorov@gmail.com

Antonis Tsintarakis, external researcher, Biomedical Applications Unit, Institute of Chemical Biology, National Hellenic Research Foundation (NHRF), 11635, Athens, The Hellenic Republic, <https://orcid.org/0009-0005-2304-6954> E-mail: tsintarakis@hotmail.com

Evangelos Kirithras, doctor, external researcher, Laboratory of toxicology and forensic sciences, Medical School, University of Crete, Heraklion, 71003, The Hellenic Republic, <https://orcid.org/0009-0007-2504-5407> E-mail: vaggelis@libero.it

Ali Taghizadehghalehjouhi, medical pharmacologist, associate professor, Medical Pharmacology faculty, Bilecik Sheikh Edebali University, Bilecik, 11230, The Republic of Turkey, <https://orcid.org/0000-0002-3506-0324> E-mail: alitgzd@gmail.com

Valerii N. Rakitskii, DSc (Medicine), professor, Academician of the RAS, Scientific Director of the Institute of Hygiene, Pesticide Toxicology and Chemical Safety, Federal Scientific Center of Hygiene named after F.F. Erisman, Mytishchi, 141014, Russian Federation, <https://orcid.org/0000-0002-9959-6507> E-mail: rakitskii.vn@fncg.ru

Сведения об авторах

Николопулу Димитра, бакалавр в области биологии (специализация: биомолекулярные науки и биотехнологии), науч. сотр., Лаборатория токсикологии и судебной медицины, Медицинская школа, Университет Крита, Ираклион, 71003, Греческая Республика. E-mail: d.nikolopoulou@uoc.gr

Карампатзакис Томас, магистр в области токсикологии, аспирант, Лаборатория физиологии животных, Кафедра биохимии и биотехнологии, Университет Фессалии, Лариса, 41500, Греческая Республика. E-mail: tkarampatzakis@uth.gr

Куретас Димитриос, профессор физиологии и токсикологии животных, Лаборатория физиологии животных, Кафедра биохимии и биотехнологии, Университет Фессалии, Лариса, 41500, Греческая Республика. E-mail: dkouret@uth.gr

Федоров Дмитрий Сергеевич, магистр в области компьютерных наук, аспирант, мл. науч. сотр., Сибирский федеральный научный центр агробиотехнологий Российской академии наук, 630501, р.п. Краснообск, Россия. E-mail: dmtry.fedorov@gmail.com

Цинтаракис Антонис, магистр в области клинической биохимии и молекулярной диагностики, внешний науч. сотр., Отдел биомедицинских приложений, Институт химической биологии, Национальный фонд исследований Греции (NHRF), 11635, Афины, Греческая Республика. E-mail: tsintarakis@hotmail.com

Кириктас Евангелос, врач, внешний науч. сотр., Лаборатория токсикологии и судебной медицины, Медицинский факультет, Университет Крита, Ираклион, 71003, Греческая Республика. E-mail: vaggelis@libero.it

Тагизадегхалехджоу Али, доктор медицинской фармакологии, доцент, преподаватель медицинской фармакологии, Университет Биледжик Шейх Эдебали, 11230, Биледжик, Турецкая Республика. E-mail: alitgzd@gmail.com

Ракитский Валерий Николаевич, доктор мед. наук, профессор, академик РАН, научный руководитель Института гигиены, токсикологии пестицидов и химической безопасности ФБУН «ФНЦГ им. Ф.Ф. Эрисмана» Роспотребнадзора, 141014, Мытищи, Россия. E-mail: rakitskii.vn@fncg.ru