MEKONG UNIVERSITY SCIENTIFIC JOURNAL
https://tapchikhdhcl.edu.vn
https://vjol.info.vn/index.php/dhcl

NANOTECHNOLOGY - THE DRIVING FORCE OF THE MEDICAL REVOLUTION IN THE ERA OF INDUSTRY 4.0

Luong Minh Cu, Vu Ba Dung*
Mekong University
**Email: vubazung305@gmail.com*

Date of submission: 26/11/2025; Review Day: 02/12/2025; Date of article approval: 15/12/2025

ABSTRACT

The fourth industrial revolution (Industry 4.0) is the driving force for sustainable development. In which nanotechnology will be strongly applied in medicine. Nanomedicine is the application of nanotechnology in human health care. Materials at the nanometer scale have very different physical, chemical and biological properties than the same material at larger scales. Nanotechnology and nanomaterials can create effective diagnostic tools and methods. Nanomedicine products can be targeted by nanorobots. The highly toxic treatments can be delivered with improved safety using nanotechnology, such as chemotherapy cancer drugs. This article is a narrative review about nanotechnology applications for the medical field in the future, which is the main motivation of medicine revolution in the industry 4.0. This review summarizes recent advances, applications, and future prospects of nanotechnology in modern medicine

Keywords: *Industry 4.0*; *Nanomedicine*; *Nanodrug*; *Nanorobot*.

1. Introduction

Nanotechnology has been transforming our lives thanks to its unique and exceptional properties. By harnessing these special characteristics, a wide range of applications across various fields has been proposed, with particularly significant impacts in medicine. Nanotechnology encompasses emerging fields such as bionanotechnology, chemical nanoparticles, and nanorobotics. It enables rapid access to diseased cells, thereby enhancing the precision and effectiveness of medical interventions. The applications of nanotechnology in medicine are crucial for disease treatment, offering multiple advantages, including rapid and accurate disease detection and diagnosis; the development of novel instruments and therapeutic techniques; targeted drug delivery directly to diseased cells with high precision; antimicrobial and anti-infection capabilities; and the ability to edit genes or diseased cells without harming surrounding healthy tissues. In the pharmaceutical world, nanotechnology applications often involve drugs formulated with active ingredients at the nanoscale. One of the most important advantages of nanoparticle based systems (1–100 nm) is their extremely small size, which significantly increases the ratio of surface molecules to total molecules. This translates into a large surface area, resulting in enhanced surface activity and altered physical and biological properties. A key advantage of nanopharmaceuticals is their ability to be delivered specifically to predetermined sites within the body using various approaches, including controlled nanorobots and autonomous nanorobots.

2. Nanotechnology: A Pivotal Technological Breakthrough Accelerating The Medical Revolution In The Age Of Industry 4.0

2.1. Nanopharmaceuticals

Nanotechnology demonstrates its remarkable advantages in medicine, particularly in the field of nanopharmaceuticals. Discoveries in nanotechnology and nano-based drug systems have significantly advanced modern pharmaceuticals, elevating healthcare to a new level. Nanoparticles possess an exceptionally high surface-area-to-volume ratio due to their nanoscale size, enabling them to carry large quantities of drugs and circulate rapidly through the bloodstream. The increased surface area enhances their mechanical, magnetic, optical, and catalytic properties, allowing nanoparticles to be widely used in drug formulations with markedly improved therapeutic efficacy [1–3]. Certain nanoparticles are photo-responsive, generating sufficient heat upon light irradiation to destroy cancer cells. Nanopharmaceuticals are considered "smart drugs" capable of controlled release via biochemical sensing; they may even be wirelessly regulated and dosage-adjusted based on real-time physiological data collected throughout the body. Nanofibers are used in wound dressings, textiles, surgical implants, tissue engineering, and artificial organs. Smart nanomaterial-based bandages can degrade or absorb into tissue once the wound has healed. In these advanced dressings, nanofibers may serve functions such as coagulation, antimicrobial activity, and even sensing to detect infectious symptoms [1–3]. For antimicrobial therapy, gold nanoparticles and gold quantum dots have demonstrated highly effective antibacterial performance. Medical nanotechnology also allows the design of more efficient drug-delivery modalities, particularly through direct targeting of diseased cells. This increases treatment outcomes while minimizing damage to healthy tissues. Likewise, nanotubes conjugated with tumor-specific antibodies can accumulate in cancerous tissues and absorb laser light, generating heat to ablate tumors [1–3]. Medical applications of magnetic nanotechnology include:

- Enhancement of magnetic resonance imaging (MRI) quality.
- Localized hyperthermia for malignant cell destruction.
- Targeted drug delivery.

Iron-oxide magnetic nanoparticles (Fe_2O_3 and Fe_3O_4) tend to aggregate when exposed to a magnetic field. In treatment, drug-loaded magnetic nanoparticles are injected intravenously; the bloodstream transports them to the diseased region, where an external magnetic field concentrates and directs them preciselyeven to anatomically challenging sites such as cerebral microvasculature or renal tubules. This enables localized tumor and cancer therapy, after which the particles may remain in the area until therapy is completed and then be cleared from the body. Intravenous delivery of magnetic nanoparticles is highly effective because once inside the body, they become coated with plasma proteins, allowing them to penetrate blood vessels and enter tissues or intracellular environments. Larger particles (50–100 nm) do not freely circulate; instead, they adhere to vascular walls and can then be magnetically guided to the desired treatment site.

Targeted drug delivery to the brain is one of the most challenging areas of biomedical research [5, 6]. A major reason is the presence of the blood brain barrier (BBB), formed by the tight junctions of microvascular endothelial cells at the interface between blood and neural tissue. This barrier severely restricts the penetration of most therapeutic molecules into the brain, limiting treatment efficacy for central nervous system (CNS) disorders such as brain tumors, Alzheimer's disease, Parkinson's disease, stroke, and others. Magnetic iron-oxide nanoparticle–based delivery systems are being extensively investigated for effective drug transport into the brain. These systems rely on magnetically guided iron oxide nanoparticles to deliver therapeutic agents across the blood brain barrier (BBB) and enable monitoring of distribution efficiency via magnetic resonance imaging (MRI) or magnetic particle imaging (Figure 1). Due to their small size, magnetic iron oxide nanoparticles exhibit high permeability and retention, allowing them to cross the BBB more effectively [7–10]. Chemotherapy remains one of the most common yet intimidating treatments for cancer, in which cytotoxic compounds are used to kill cancer cells. However, these compounds often disrupt essential life-sustaining processes in healthy cells as well, because the drugs circulate systemically and reach most organs.

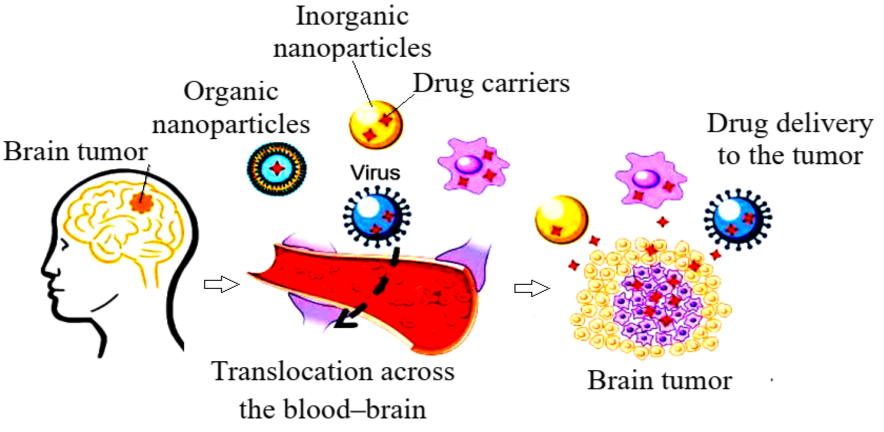

Figure 1. Schematic illustration of therapeutic molecules crossing the blood brain barrier facilitated by magnetic iron oxide nanoparticles or magnetically guided viral vectors [9].

For this reason, a major focus of contemporary cancer therapy research is the development of strategies that selectively target drugs to tumors while sparing normal tissues. Among these strategies, the use of external magnetic fields to concentrate magnetically responsive nanodrugs or drugs conjugated to magnetic nanoparticles at tumor sites has gained considerable attention. This magnetically guided targeting approach allows therapeutic agents to be accumulated specifically within the tumor. Consequently, a much lower dosage of cytotoxic drugs is required, limiting systemic distribution and reducing exposure of healthy tissues to harmful chemotherapeutic agents [7–10].

A novel approach involves the use of magnetotactic bacteria, which can be guided by external magnetic fields to transport therapeutic agents directly to tumor sites. Under a rotating magnetic field, these magnetically responsive bacteria are able to overcome cellular barriers and effectively penetrate tumor tissues (Figure 2). Targeted drug delivery to the brain remains one of the most challenging areas of biomedical research [4–6]. A major obstacle is BBB, formed by microvascular endothelial cells at the interface between blood and neural tissue. This barrier significantly restricts the entry of many therapeutic molecules into the brain, limiting treatment efficacy for various central nervous system (CNS) disorders, including brain tumors, Alzheimer's disease, Parkinson's disease, stroke, and others. Magnetic iron-oxide nanoparticle-based delivery systems are being widely investigated to achieve efficient transport of drugs into the brain. Due to their small size, iron-oxide nanoparticles exhibit high permeability and retention, enabling them to cross the BBB more effectively [7–10]. Magnetic iron oxide nanoparticles are also directly applied in cancer therapy through magnetic hyperthermia. In this technique, an external magnetic field is used to concentrate the nanoparticles at the tumor site, after which an alternating magnetic field is applied to heat the particles to temperatures of 42–47°C. This localized heating selectively destroys malignant cells within the tumor. Compared with chemotherapy, magnetic-field-induced hyperthermia offers significant advantages, as it specifically targets the tumor without damaging surrounding healthy tissues, thereby improving therapeutic outcomes. Additionally, cancer cells are more sensitive to elevated temperatures than normal cells [7–10]. One of the most prominent nanomaterials in medical nanotechnology is silver nanoparticles (AgNPs). These particles are typically smaller than 100 nm and contain approximately 20–15,000 silver atoms. At the nanoscale, silver exhibits unique physical, chemical, and biological behaviors. Because of their strong antimicrobial activity, silver nanoparticle coatings are widely used for the treatment of wounds and burns. AgNPs demonstrate broad-spectrum antibacterial effects against both Gram-negative and Gram-positive bacteria, as well as antibiotic-resistant strains [11, 12]. Their antimicrobial efficacy depends on both concentration and particle size: higher concentrations yield stronger antibacterial effects, whereas smaller nanoparticles can exert bactericidal activity even at very low concentrations. These nanoparticles attach to and penetrate bacterial cell walls, disrupting membrane integrity. Silver nanoparticles are also effective antifungal agents, active against multiple fungal species. Their antifungal mechanism is associated with membrane disruption and inhibition of budding processes. At a concentration of 0.1 mg/L (0.1 ppm), AgNPs exhibit strong antifungal activity. Additionally, silver nanoparticles possess antiviral properties, showing inhibitory effects against HIV-1, hepatitis B virus, respiratory syncytial virus, herpes simplex virus, and smallpox virus. The antiviral mechanism of silver nanoparticles is attributed to their ability to inhibit multiple stages of the viral life cycle. AgNPs are considered broad-spectrum antiviral agents effective against numerous viral strains, with minimal likelihood of inducing resistance. Silver nanoparticles are also widely applied in the diagnosis of cardiovascular diseases and cancer, enabling early detection of atherosclerotic features and cardiovascular abnormalities at both the molecular and cellular levels. In medical practice, silver nanoparticles are used in: sterilization of instruments and hospital rooms; wound care; prevention of infectious disease transmission; cardiovascular implants (e.g., silver-nanocoated silicone artificial hearts); and various dental treatments [11, 12]. Gold nanoparticles (AuNPs), depending on their size and morphology, are employed for different biomedical purposes. Their medical applications include photothermal therapy, targeted delivery, drug transport, imaging enhancement, nucleic acid delivery, toxin and pathogenic agent removal, and use as vaccine or immunotherapy adjuvants [13–15].

2.2. Nano diagnostics

Diagnostic or therapeutic agents engineered with the assistance of nanomaterials can overcome biological barriers to access molecular targets, modulate molecular interactions, and monitor microenvironmental changes [16]. Nanomaterials can be fabricated in diverse shapes, sizes, compositions, surface chemistries, and porous or solid structures based on their tunable optical, electronic, magnetic, and biological properties [17]. These features qualify nanomaterials for important applications in medical diagnostics [18, 19]. Molecular diagnostics play an essential role in the advancement of modern medicine, particularly in point-of-care testing. In such diagnostic platforms, nanoscale probes are ideal tools for analyzing the detailed components of living cells. For combined diagnosis and therapy (theranostics), implantable nanoscale devices may serve as early detection and preventive diagnostic tools. The application of nanotechnology in molecular diagnostics offers key advantages, including the requirement for only a minimal sample volume while providing faster and more sensitive detection. Several types of nanoparticles have been utilized in molecular-level disease diagnostics. Among them, quantum dots (QDs) are the most frequently employed. These inorganic CdSe nanocrystals (comprising approximately 200–10,000 cadmium selenide atoms), coated with ZnS, emit fluorescence when excited with low-energy light. The size of a quantum dot determines the wavelength (color) of emitted light. QDs are widely used in genetic profiling and have significant potential applications in cancer diagnostics [20–22]. In nano diagnostics, nanoparticles often need to be coupled with additional systems, such as nanorobots or molecular motors, to perform complex biomedical tasks. Fluorescent nanoparticles or drug loaded nanocarriers can be engineered and guided to function as self-propelled nano-motors, autonomously navigating to specific sites in the body for diagnostic or therapeutic purposes [23, 24].

2.3. Medical Nanorobots

Biomedical nanorobots are highly miniaturized and specialized devices capable of performing precise tasks within the human body. Nanorobots can function as drug-delivery vehicles with their own propulsion mechanisms, enabling precise navigation, tissue penetration, and targeted drug release at designated sites. In surgical applications, nanorobots have enabled clinicians to reduce the invasiveness of conventional procedures while maintaining superior precision, flexibility, and consistent control throughout the operation. Nanorobots have also demonstrated the ability to perform accurate disease diagnostics by isolating and detecting a wide range of biological targets, from proteins to nucleic acids and cancer cells. Specialized nanorobots can be engineered to enter the bloodstream directly (Figure 9). Once circulating in blood, these nanobots can monitor concentrations of blood components and alert healthcare providers to the early presence of potential diseases. This technology holds particular promise for patients with diabetes, as nanorobotic devices could be used to continuously track blood glucose levels and signal when glucose concentrations fall to dangerously low or high levels.

3. Conclusion

In the era of Industry 4.0, a transformative revolution in healthcare is being driven by nanotechnology. Nanotechnology addresses critical challenges in targeted therapeutic management, reduces the risk of side effects, and maximizes treatment efficacy including in cancer therapy through gene-based approaches. Among the most promising innovations in nanomedicine is the development of nanorobots. Their applications span multiple fields, such as vaccine generation, targeted drug delivery, wearable medical devices, diagnostic and imaging technologies, and antimicrobial products. Nanotechnology serves as a powerful engine for advancing more effective pharmaceuticals and enabling improved diagnostic tools for the early detection of various diseases. Nanomaterials including magnetic nanoparticles, silver nanoparticles, and gold nanoparticles play a central role in the development of highly efficient nanotherapeutics. Overall, nanotechnology stands as one of the key driving forces behind the medical revolution of Industry 4.0 era.

REFERENCES

A. Haleem, M. Javaid, R. Pratap Singh, S. Rab, R. Suman (2023), Applications of nanotechnology in medical field: a brief review, *Global Health Journal*, *7*(2), pp. 70–77.

S. Malik, K. Muhammad and Y. Waheed (2023), Emerging Applications of Nanotechnology in Healthcare and Medicine, *Molecules*, *28*(18), p. 6624.

H. Ibrahim (2020), Nanotechnology and Its Applications to Medicine: an overview, *QJM: An International Journal of Medicine*.

L. L. Israel, A. Galstyan, E. Holler, J. Y. Ljubimova (2020), Magnetic Iron Oxide Nanoparticles for Imaging, Targeting and Treatment of Primary and Metastatic Tumors of the Brain, *Journal of Controlled Release*, *320*, pp. 45–62.

R. R. Qiao, C. H. Yang, M. Y. Gao (2009), Superparamagnetic Iron Oxide Nanoparticles: From Preparations to in vivo MRI Applications, *Journal of Materials Chemistry*, *19*, pp. 9286–9296.

M. Jeon, M. V. Halbert, Z. R. Stephen, M. Zhang (2021), Iron Oxide Nanoparticles as T1 Contrast Agents for Magnetic Resonance Imaging: Fundamentals, Challenges, Applications, and Prospectives, *Advanced Materials*, *33*, p. 1906539.

A.G. Roca, R. Costo, A.F. Rebolledo, S. Veintemillas Verdaguer, P. Tartaj, T. Gonzalez-Carreno, M.P. Morales, C.J. Serna (2009), Progress in the Preparation of Magnetic Nanoparticles for Applications in Biomedicine, *J. Phys D Appl Phys* 42, p. 224002.

H. Wei, et. Al. (2017), Exceedingly Small Iron Oxide Nanoparticles as Positive MRI Contrast agents, *PNAS* 114 (9), pp. 2325-2330.

H.E. Daldrup-Link (2017), Ten Things You Might Not Know about Iron Oxide, *Nanoparticles Radiology* 284, pp. 616-629.

B. Wilson (2019), Drug Targeting Strategies into the Brain for Treating Neurological Diseases, *J. Neurosci Meth* 311, pp. 133-146.

V. P. Sameena, J. E. Thoppil (2022), Green synthesis of silver nanoparticles from Euphorbia and its biological activities, *Nanotechnology for Environmental Engineering* 7(1), pp. 277-392.

I. X. Yin, J. Zhang, I. S. Zhao, M. L. Mei, Q. Li, C. H. Chu (2020), The Antibacterial Mechanism of Silver Nanoparticles and Its Application in Dentistry, *International Journal of Nanomedicine*, pp. 2555–2562.

Z. Yang, H. Liu, M. Hao, S. Kan, D. Liu, W. Liu (2022), The Applications of Gold Nanoparticles in the Diagnosis and Treatment of Gastrointestinal Cancer, *Sec. Cancer Genetics* 11, https://doi.org/10.3389/fonc.2021.819329.

S. Bagheri, M. Yasemi, E. Safaie-qamsari, J. Rashidiani (2018), Using gold nanoparticles in diagnosis and treatment of melanoma cancer, *Artificial Cells, Nanomedicine, and Biotechnology* 46(1), pp.1-10.

J. Milan, K. Niemczyk and M. Kus-Liśkiewicz (2022), Treasure on the Earth-Gold Nanoparticles and Their Biomedical Applications, *Materials* 15(9), p.3355. M. Chakravarty, A. Vora (2021), Nanotechnology-based antiviral therapeutics, *Drug Deliv. Transl. Res.* 11, pp. 748–787.

E. Fattal, F. Fay (2021), Nanomedicine-based delivery strategies for nucleic acid gene inhibitors in inflammatory diseases, *Adv. Drug Deliv. Rev.* 175, p. 113809.

M. Singh (2018), Application of Metallic Nanomaterials in Nanomedicine, *Adv. Exp. Med. Biol.*1052, pp.83–102. M. Zhou, Y. Zhou, Y. Cheng, Y. Wu, J. Yang, Z. Lv (2020), Application of Gold-Based

Nanomaterials in Tumor Photothermal Therapy and Chemotherapy. *J. Biomed.Nanotechnol.* 16, pp. 739–762.

T. Kubik, K. Kubik and M. Sugisaka (2005), *Cur. Pharma. Biotechnol***.** 6, pp. 17-33.

S. Rosenthal (2001), Bar-coding biomolecules with fluorescent nanocrystals, Nat.Biotechnol. 19, pp.621-622.

M. Han, X. Gao and J.Z. Su (2001), Nanotechnology on Duty in Medical Applications, *Nat. Biotechnol.* 19, pp.631- 635.

H. Jiang, N. Yoshinaga, M. Sano (2010), Active motion of a Janus particle by self-thermophoresis in a defocused laser beam, *Physics Review Letters* 105, p. 268302.

M. Yang, M. Ripoll (2014), A self-propelled thermophoretic microgear, *Soft Matter* 10, p.1006.