

Prospects and Challenges of Nanotechnology in the Treatment of Pediatric Diseases

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Abstract

As a new approach, nanotechnology has opened up new horizons in disease diagnosis and treatment. Nanotechnology, utilizing nanomaterials and targeted drug delivery systems, has addressed numerous challenges in treating pediatric diseases. Pediatric diseases present unique challenges in treatment management due to the specific physiological characteristics of this age group, including the need for accurate drug dosages, minimizing side effects, and enhancing treatment efficacy. Nanotechnology offers groundbreaking applications in the diagnosis and treatment of childhood diseases, providing targeted therapies with enhanced efficacy and reduced side effects. Key applications include nano-drug delivery systems for the precise treatment of pediatric cancers (e.g., leukemia and brain tumors), nanosensors for the early detection of metabolic and infectious diseases, and nanoparticle-based inhalable therapies for respiratory conditions such as asthma. Additionally, nanotechnology enables improved bioavailability and reduced drug dosages, critical for pediatric patients. However, challenges such as long-term safety, biocompatibility, and regulatory hurdles remain. Future directions include the development of multifunctional nanoplatfoms for combination therapy and personalized medicine, alongside advances in scalable and cost-effective manufacturing. Addressing these challenges will be essential for translating nanomedicine into mainstream pediatric healthcare.

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1. Introduction

Nanotechnology, one of the most advanced interdisciplinary sciences of the present era, is revolutionizing scientific and technological approaches in various fields, including medicine, by studying and utilizing materials

at the nanometer scale [1-3]. At the nano scale, materials exhibit different physical, chemical, and biological properties compared to those at larger dimensions [4, 5]. These differences are attributed to the increased contact surface area relative to volume, quantum mechanics, and variations in molecular behavior [6]. These have provided new opportunities for developing new methods of diagnosing and treating diseases, especially in children. Nanotechnology has become an irreplaceable tool for creating targeted medical therapeutic methods due to its ability to manipulate molecules [7, 8].

One of the most critical applications of nanotechnology is the use of nanoparticles as drug carriers that can deliver drugs directly to the site of injury or diseased cells without harming healthy cells [9, 10]. This feature is significant in the treatment of diseases such as cancer. In addition, nanobiosensors have also made a substantial impact in the early diagnosis of diseases, particularly cancers and infectious diseases. Beyond improving treatments, nanotechnology has also enabled the design of new biomaterials that can interact directly with the body's biological systems [11]. Biocompatible nanoparticles interact with cells and biological molecules, regenerating damaged tissues or improving the body's immune responses [12]. Additionally, with the aid of nanotechnology, new vaccines have been developed that can stimulate the immune system more precisely and effectively [13, 14], which is particularly crucial in preventing pediatric diseases.

Another key aspect of nanotechnology is its ability to design innovative drug-delivery systems. Drug-delivery systems can release the drug only in the presence of specific biological signals, increasing the treatment's effectiveness and minimizing side effects [15]. This technology is of particular importance in chronic and genetic diseases of children, which require long-term therapies [16-18].

Despite its many advantages, nanotechnology still faces challenges. Concerns exist regarding the safety, toxicity, and environmental impact of nanoparticles [19]. Mass production and cost reduction are other obstacles to the widespread use of this technology. However, scientific advances in this field hold a bright prospect for widespread nanotechnology applications in medicine, particularly in the treatment of pediatric diseases [20-22]. This review article examines recent advances in the use of nanotechnology for the treatment of pediatric diseases. The primary focus is pediatric diseases, including cancers, genetic diseases, and infections.

2. Nanotechnology-Based Drug Delivery

Nanotechnology has made significant contributions to medicine, and one of the most critical advances in nanotechnology is the process of targeting drugs to cancer cells [23]. Nanoparticles can act as a carrier, transporting anticancer drugs directly from a fixed point to the cancerous tumor [24]. A key aspect of this process is that it recognizes specific features of cancer cells, such as their surface receptors or the acidic environment in which they are found [25]. The mechanism by which these nanoparticles can target cancer cells involves modifying them with recognition molecules or ligands, such as antibodies or peptides, that are specifically compatible with cancer cells [26, 27]. For children with cancer, this technique is beneficial, as the drug does not need to be distributed throughout the body in an unnecessarily irritating way, which enables the drug to be as effective as possible (Figure 1).

2.1 Drug nanocarriers for chemotherapy and radiotherapy

Chemotherapy and radiotherapy are two of the most effective cancer treatments [28]. Still, their effectiveness is rarely matched by the harm they can do to healthy tissues due to their damaging nature. Several nanocarriers can

be used to deliver chemotherapy drugs to tumor cells, which can be controlled or delivered at lower radiation doses and using effective methods, such as lipid nanoparticles, biodegradable polymers, and metal nanoparticles [29, 30]. The use of nanoparticles in radiotherapy has also led to a revolution in this treatment, as they possess unique properties that enable them to enhance radiation absorption in tumors and improve the performance of the treatment method. Having this feature is highly crucial in children, whose bodies are particularly susceptible to radiation therapy because of their genetic structure [31, 32].



Figure 1. A summary of the factors impacting pharmacotherapy practice and the development of therapeutics aimed at pediatric patients [33]

2.2 The role of nanotechnology in reducing the side effects of traditional treatments

There are several advantages to using nanotechnology to treat pediatric cancers, one of which is its ability to prevent unwanted side effects associated with conventional treatment methods, thereby reducing the severity of

these side effects [34]. As a result of traditional chemotherapy, drugs are distributed systemically throughout the entire body, resulting in damage to both healthy cells and cancer cells during the chemotherapy process [35]. As a result, dehydration can lead to problems such as a weakened immune system, hair loss, or digestive issues. Using nanocarriers as a delivery system saves both healthy tissue and reduces the side effects of chemotherapy to a significant extent, as nanocarriers can deliver drugs precisely to tumor cells, thereby reducing damage to healthy tissues [36]. A considerable advantage of nanotechnology is that it enables the use of lower doses of drugs, which is particularly advantageous for children, as their immune systems are more sensitive than those of adults. Besides enabling innovative approaches, nanotechnology also facilitates the development of more creative approaches, such as nanoparticles that can respond to stimuli [18]. The activation of these nanoparticles occurs only when specific signals, such as temperature, pH, or certain enzymes present in the tumor, are detected, which reduces the possibility of adverse side effects [28, 37]. Due to this development, children with cancer now have access to highly effective treatments with lower risks as a result of their treatment (Figure 2).

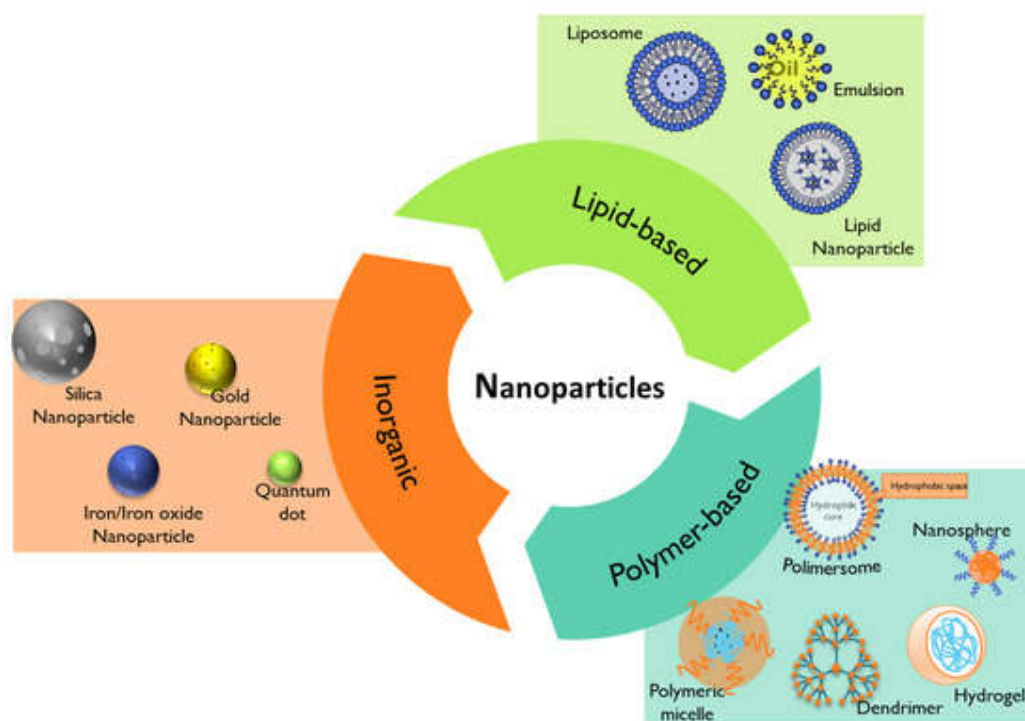


Figure 2. Summary of the different types of nanoparticles that can be used in nanomedicine [28]

3. Applications of Nanotechnology in the Treatment of Genetic Diseases in Children

It is becoming increasingly common in genetic research to use nanoparticles in gene editing methods (CRISPR/Cas9) [38]. Genome editing using CRISPR/Cas9 technology is one of the most innovative ways to treat genetic diseases [39]. Using this technology, scientists can identify and correct defective genes with high precision and accuracy [40]. Nevertheless, this method presents several challenges, including the transfer of the Cas9 system to target cells, which is a primary hurdle. With the help of nanoparticles, this editing tool can be delivered effectively to various tissues and organs. Using nanoparticles, which can be made of several materials, including lipids, biocompatible polymers, and metal nanoparticles, CRISPR/Cas9 is delivered to the target cells by

preventing the destruction of the gene or its inactivation along the way [41, 42]. As a result of this approach, significant progress has been made, particularly with children, where genetic modification can have a lasting impact on their development [43, 44].

3.1 Gene transfer

Nanocarriers play a crucial role in delivering genes to target cells, thereby enabling the treatment of genetic diseases [45]. Using this method, a healthy gene is replaced with a defective gene, or a defect is altered so that it functions as it was designed to. Nanocarriers are highly efficient tools for gene transfer due to their small size, biocompatibility, and ability to carry a large amount of genetic information [33, 46]. In addition to carrying genetic cargo, nanocarriers can deliver it harmlessly and effectively to cells. Moreover, nanoparticles can also cross biological barriers, including cell membranes and the blood-brain barrier, which is particularly important for treating neurological genetic diseases in children and other non-transferable diseases [47].

3.2 Treatment of rare genetic diseases with nanotechnology-based approaches

The diagnosis of rare genetic diseases, which are often diagnosed in children, is considered a significant challenge in medicine due to their complexity, along with the lack of effective therapeutic options available [48]. Using nanoparticles, small interfering RNAs (siRNAs) can be delivered directly to targeted cells, inhibiting their expression in healthy cells or delivering healthy genes directly to diseased cells [49, 50]. Furthermore, it has been demonstrated that utilizing this technology enables the development of new nanomedicines that can target defective proteins with precision [51]. It has been shown that nanotechnology is an effective tool for treating rare genetic diseases, owing to its ability to be tailored to each individual's specific needs [52, 53]. Using nanotechnology, treatments can be tailored to the specific type of defective gene and the patient's unique characteristics, thereby providing the best possible outcome [6, 54]. There are several advantages to this personalized approach, especially for children with a range of genetic characteristics and unique physiological conditions. As a result of the use of nanotechnology in the treatment of genetic diseases in children, treatment effects are improved, and the side effects are reduced [35, 55].

4. Nanoantibiotics and Antimicrobial Resistance

A significant challenge facing the treatment of infections today is the increasing resistance of bacteria to antibiotics [56, 57]. There is an increased importance of this issue in children, mainly due to the weakened immune systems of these children and the need for more effective medicines and safer treatments. By developing nanoantibiotics, nanotechnology has contributed to the creation of new solutions to overcome the problem of antibiotic resistance [58-60]. In particular, metal nanoparticles, such as silver and gold, possess potent antimicrobial properties, as they can disrupt the function of vital enzymes within bacterial cells and destroy their cell walls [61, 62]. A combination of nanoparticles and traditional antibiotics may enhance the effectiveness of both drugs and reduce microbial resistance by increasing their effectiveness and reducing their side effects [63-65]. As a result of these methods, children with complex infections can be treated more effectively, particularly when these methods are employed (Figure 3).

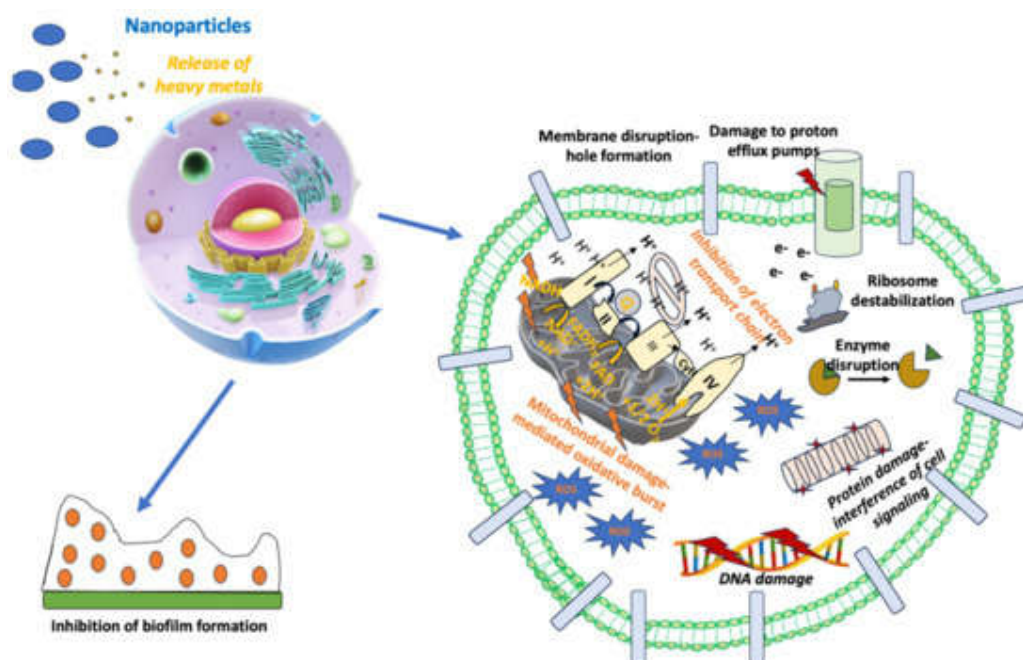


Figure 3. Mechanism of action of nanoparticles in the treatment of infectious diseases [66]

4.1 Nanobiosensors for rapid detection of infections

When children are infected with an infection, detecting it as early as possible is crucial, especially if their symptoms worsen rapidly. Nanobiosensors are among the most effective tools for diagnosing infections, as they are highly sensitive and can detect biomolecules at very low concentrations [67-69]. With metal nanoparticles, magnetic nanoparticles, or quantum dots, it is possible to quickly detect biomarkers of bacterial, viral, or fungal infections with nanobiosensors [70-73]. Nanobiosensors, for example, can detect specific proteins or DNA of viruses within minutes of swabbing a child's blood or urine, providing results with the same level of detail [74].

4.2 Application of nanotechnology in the development of new vaccines

As a preventive measure, vaccinations are crucial for protecting children against infectious diseases; however, producing safe and effective vaccines remains a significant challenge. Using nanotechnology as an enabler, scientists have developed new, more effective vaccines utilizing nanocarriers and various materials [75, 76]. A key aspect of nanoparticles is that they serve as carriers that deliver antigens to immune cells, thereby triggering a more robust immune response [77-79]. Using nanoparticles and reducing the vaccine dose needed can also provide longer-lasting immunity.

One of the key advances in this field is that RNA vaccines based on lipid nanoparticles have proven highly successful in viral diseases, such as COVID-19 [80-82], and could also be used in pediatric infections. Using nanoparticles in vaccines can also simplify their administration, eliminating the need for injections and allowing for vaccines that can be administered orally or inhaled.

5. Challenges

One of the biggest challenges in using nanotechnology to treat pediatric diseases is concerns about the toxicity and long-term effects of nanomaterials [83, 84]. The very small size of nanoparticles may allow them to penetrate deep tissues and even cross the blood-brain barrier, which can cause unknown complications in the developing bodies of children [85]. Further studies are needed to evaluate the safety of nanomedicines in the pediatric population. Some drug nanocarriers may cause immune or inflammatory reactions in children. Since the immune system of children is still developing, their body's response to nanomaterials may differ from that of adults. Additionally, the breakdown and excretion of nanoparticles in children's bodies must be carefully studied to prevent their accumulation in vital organs.

There is no specific regulatory framework for pediatric nanomedicines, and the approval process for these treatments is slow and complex. The lack of global standards for assessing the quality, efficacy, and safety of pediatric nanomedicines has hampered their clinical development [86, 87]. International collaboration is crucial for establishing standardized protocols. Producing nanomedicines of consistent quality on an industrial scale is challenging, particularly for complex formulations, such as targeted nanocarriers [88]. The high cost of research, development, and production of these technologies may also limit access to nanotherapeutics in low-income countries, where children are most in need of effective treatments. The use of novel technologies, such as nanomedicines, in children is associated with ethical concerns, including worries about informed consent and parental concerns regarding unknown side effects. Additionally, a lack of adequate awareness among physicians and the public about the benefits and risks of nanotechnology may hinder the adoption of these methods. Education and transparency play a key role in addressing this challenge.

6. Future

It is essential to consider the safety of nanoparticles when applying nanotechnology to pediatric medicine. Additionally, it is necessary to assess the long-term effects of these nanoparticles. Since nanoparticles are small and possess unique chemical properties, they may accumulate in sensitive tissues such as the brain and liver, causing unforeseen complications [89, 90]. Children whose bodies are still in the process of developing may be at even greater risk of serious health problems. The toxicity of metal nanoparticles, such as gold and silver, is also a concern, and further studies are needed to fully understand their environmental and biological effects before they can be used for human purposes [91, 92]. Furthermore, the possibility of unreported and unauthorized use of nanoparticles is among the ethical issues that need to be considered, as well as the issue of equitable access to this technology.

Nanoparticles have a wide range of applications in medicine, but the most challenging aspect is creating nanoparticles in large numbers at a cost-effective and efficient cost [93]. It may be challenging for patients with limited resources to afford the complex and precise processes required to produce high-quality nanoparticles, as these processes are expensive and time-consuming. Consequently, nanotechnology may be more challenging for patients with limited resources [94]. This concept is particularly crucial, especially in pediatric medicine, where there is a significant need to develop drugs and treatments that are more specific and safer. Furthermore, there is currently no standardization of methods for large-scale nanoparticle production, and a lack of control over nanoparticle quality could hinder the advancement of this technology in practical applications.

Nanotechnology is expected to have a significant impact on pediatric medicine in the years to come [95]. Researchers are already developing ways to address current obstacles. Future research will focus on creating more

biocompatible and degradable nanoparticles that can be eliminated from the body after fulfilling their intended purpose [34]. This will avoid accumulation or toxic build-up in the tissue. Furthermore, new technologies such as 3D printing of nanoparticles and more efficient synthesis methods driven by these advancements can improve production methods and reduce costs. This makes this technology more accessible to a broader audience.

There is also a possibility of using artificial intelligence to design nanoparticles with optimal properties [96]. A new method of targeting tumor cells more precisely and causing fewer side effects can be developed using big data and simulation models to design nanoparticles. Combining nanotechnology with advanced biomaterials and biotechnology can create more effective tools and therapies, including advanced biosensors and better nano-vaccines. While numerous ethical, safety, and financial challenges exist, nanotechnology has the potential to transform pediatric medicine in the coming decades. To solve the current problems, researchers, clinicians, the pharmaceutical industry, and policymakers must collaborate to develop solutions. The increasing investments in research and development, standardization, and public education made in nanotechnology over the last decade are expected to make nanotechnology a significant player in improving children's health in the years to come.

7. Conclusion

Nanotechnology plays a vital and innovative role in treating pediatric diseases, having made significant advances, particularly in various fields such as cancer, genetic disorders, and infectious diseases. This technology, utilizing nanoparticles, nanocapsules, and nanobiosensors, can deliver drugs to damaged tissues in a targeted manner and minimize the side effects of treatments. In addition, nanotechnology has enabled new capabilities in the early detection of diseases, gene modification, and molecular therapies, which can lead to a significant transformation in therapeutic approaches for rare and complex diseases in children. However, further research is needed on the safety, long-term complications, and efficacy of these methods in young patients to fully harness the potential of nanotechnology in treating pediatric diseases.

Conflicts of Interest

The authors declare no conflict of interest associated with this manuscript.

Declaration of the Use of Generative AI

After the content was fully written, an AI-powered tool was exclusively used to review and refine the chapter's grammar, punctuation, and overall linguistic flow. The AI tool was used strictly as a proofreading and language refinement assistant and was not employed at any stage for generating content, ideas, or writing chapter sections.

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