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TARGETED THERAPEUTICS: THE ROLE OF NANOMATERIALS IN CONTROLLED DRUG DELIVERY AND THERANOSTICS

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ABSTRACT

The discipline of nanotechnology relies heavily on nanomaterials, particularly in healthcare applications where they have shown great promise in enhancing medication delivery methods. Adverse side effects, low solubility, weak stability, ineffective transmembrane transport, and a short plasma half-life are only a few of the drawbacks of traditional pharmacological therapy. Conventional treatments are less effective as a result of these issues, particularly for complex disorders. To overcome these limitations, the study aims to investigate and assess how nanomaterials can enhance medication delivery and therapeutic outcomes. The emphasis is on how nanomaterials' special biological and physicochemical characteristics, such as their adaptability in terms of size, carrier, and shape capacity, allow them to efficiently transport both polar molecules and non-polar molecules. The different kinds of nanoparticles utilized in clinical settings, their interactions with biological systems, and the methods used to treat illnesses like cancer, infections, autoimmune diseases, cardiovascular diseases, and neurodegenerative conditions are also covered in this study. The results demonstrate how a better understanding of the characteristics of nanoparticles and their biological interactions can result in more precise, efficient treatments, which will ultimately improve illness diagnosis and management, especially for disorders that are currently challenging to treat or control.

Keywords: Nanomaterials, drug delivery, therapeutic applications, diagnosis

1. INTRODUCTION

A new area, referred to as "nanomedicine" has been established, which uses nanotechnology to diagnose and treat illnesses. Nanodevices and nanomaterials are the two main categories of nanotechnology. Microarrays are examples of nanodevices, which are minuscule devices at the nanoscale [1,2]. Materials with at least one dimension between 1 and 100nm are referred to as nanomaterial. The nanostructure design system uses an interdisciplinary approach to create materials at the nanoscale (figure 1). Nanotechnology is a prime example of emerging technology, showcasing designed nanomaterials that hold great potential for creating products with significantly improved performance [3]. Using medicinal ingredients at the nanoscale level creates nanomedicines. The fields of medication delivery, tissue engineering, biosensors, and nanobiotechnology have all benefited from the advancement of nanoparticles in biomedicine [4].

A brand-new field known as "nanomedicine" has emerged, which uses nanotechnology to identify and treat diseases. The two primary subcategories of nanotechnology are nanodevices and nanomaterials. Nanodevices, which are extremely small devices at the nanoscale, include microarrays [1,2]. Materials with at least one dimension between 1 and 100nm are referred to as nanomaterials. To produce materials at the nanoscale, the nanostructure design system employs an interdisciplinary approach [figure 1]. An excellent illustration of an emerging technology is nanotechnology, which features engineered nanoparticles with enormous promise for producing goods with noticeably better performance [3]. Nanomedicines are made by using therapeutic substances at the nanoscale level. The development of nanoparticles in biomedicine has helped the domains of drug delivery, tissue engineering, biosensors, and nanobiotechnology [4].

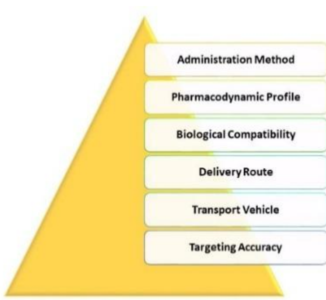

Fig.1. Nanostructure Design System

Nanoparticle-based drug delivery methods improve cancer treatment by providing better pharmacokinetics, accurately targeting tumor cells, reducing side effects, and overcoming drug resistance [5]. The physicochemical characteristics of the medications determine which nanoparticles are best for drug delivery. Research on the combination of nanoscience with bioactive natural substances is becoming more and more popular. For the administration of organic substances in the therapy of cancer and other illnesses, this strategy has several benefits. Natural compounds' medicinal properties, including their ability to serve as antibacterial agents and induce tumor-suppressing autophagy, have been extensively studied.

Using large-sized materials for drug administration presents a number of challenges, including restricted solubility, low bioavailability, inadequate tissue absorption, and instability in vivo. There are also problems with consistent efficacy, target-specific administration, and possible side effects of the medications. Thus, creating novel medication delivery methods that target particular body areas may be a practical way to deal with these pressing problems [6].

In recent years, a variety of successful drug delivery methods have been employed. Many issues still need resolution, and advanced technology is essential for efficiently delivering drugs to their target areas. Current research is looking into nano-based drug delivery systems to help in the development of medication delivery technology.

The main objectives of research on nanomaterials in delivery of drugs include improved safety and biocompatibility, reduced toxicity while preserving therapeutic effects, improved precision in drug targeting and distribution, and expedited development of new and safe medications [7].

New opportunities for tackling today's human problems have been created by the use of nanotechnology. Due to the growing influence of nanotechnology in numerous industries over the past few decades, the use of nanomaterials has dramatically expanded across a range of sectors. Nanotechnology has been especially advantageous to the pharmaceutical and medical sectors, leading to the launch of novel products [8]. Nanomedicine primarily focuses on the rapid advancement of theories, instruments, nanoscale techniques, and nanostructures specifically designed for disease diagnosis, prevention, and therapy. Direct contact between nanoparticles and the human body has resulted from their use in medicinal procedures [9].

Within minutes, the administered nanoparticles are methodically absorbed and can be eliminated from the body. Nanoparticles coated with cell membranes can withstand damage for several hours. Protein nanoparticles offer numerous benefits that make them particularly intriguing. These advantages include easy access to resources, renewability, affordability, and biocompatibility. They are also biodegradable and possess multiple functional groups that can carry high doses of drugs. Additionally, their ability to simultaneously link targeting groups allows for targeted delivery to specific cells or tissues [10, 11].

Through a variety of methods, such as intended distribution, regulated release, enhanced stability, and improved pharmacokinetics, nanoparticles (NPs) improve medication delivery. To improve drug formulation and delivery nanoparticles, properties and sizes of nanoparticles need to be carefully considered. [12].

Because nanomedicine promises to provide efficient, customized drug delivery systems that can treat complicated medical diseases, its application is growing quickly. Conventional drug delivery techniques frequently fall short of offering the accuracy required for focused therapy, which can lead to less than ideal therapeutic results and possible adverse effects. However, by making it possible to administer therapeutic chemicals in a focused and regulated manner, nanomedicine provides an answer. In the treatment of chronic and complicated illnesses like cancer, type 2 diabetes, coronary artery disease, asthma, pulmonary TB, Parkinson's illness, and Alzheimer's disease, this is very important. To properly manage or treat these disorders, more advanced and individualized techniques are frequently needed. Given the expanding potential of nanotechnology in healthcare, this research is essential to comprehending how nanomedicine can increase treatment efficacy, get beyond present drug delivery barriers, and eventually offer better ways to manage chronic conditions. The findings of this study will advance nanomedicine and enhance patient care by fostering the ongoing development of innovative drug delivery techniques.

2. NANOMATERIALS-BASED DRUG DELIVERY SYSTEM

Nanotechnology is an essential tool that can help address the limitations of traditional drug delivery methods, and it has demonstrated many beneficial applications in research and medicine for both diagnosis and treatment. The sizes, shapes, and surface characteristics of the nanoparticles employed in medical treatments are specific because these elements have a significant impact on the power of nano-drug delivery and control therapeutic efficacy [13].

Drugs that are put into nanoparticles (NPs) can interact with them chemically through hydrophobic or electrostatic interactions, or they can be physically dissolved by encapsulation. As nano-drug delivery systems, nanoparticles can enhance the solubility and stability of drugs, increase the duration of their circulation, facilitate their uptake by targeted cells or tissues, and slow down enzyme degradation. In the end, these traits result in increased medication efficacy and safety [14]. Nanoparticles (NPs) provide a distinct advantage in the diagnosis and treatment of cardiovascular diseases (CVDs) and other ailments because they are an accurate, effective, and regulated way to deliver medications intracellularly. There are various methods for delivering drugs [figure 2].

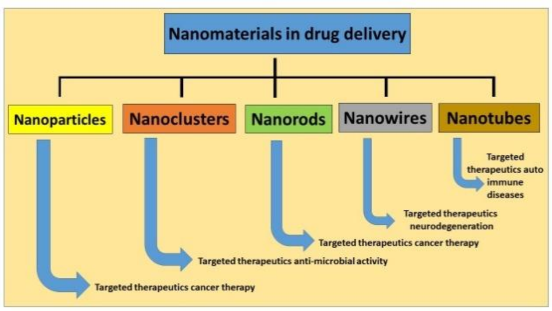

Fig.2. Nanomaterials in drug delivery

2.1. Nanoparticles

Utilizing materials at the nanoscale, like biocompatible nanoparticle [15] and nanorobots [16], are utilized for a variety of purposes, such as diagnosis [17], delivery [18], sensory [19], or purposes of actuation in a living organism [20]. Nanomedicine is a branch of medicine that applies the science of nanotechnology to treat and prevent a variety of diseases.

Metallic, metal oxide, and sulfide nanoparticles are among the natural products that have been used to create nanoparticles. It has been observed that these nanoparticles are produced by a diversity of microorganisms, including t, fungi, bacteria, and algae [21]. They present a promising formulation for administering ocular medication, featuring enhanced mucoadhesive properties while maintaining antibacterial activity. Because they may efficiently carry medications and provide increased permeability and retention (EPR) effects, nanoparticles (NP) with a diameter between 10 and 100 nm are generally regarded as suitable for cancer treatment. smaller particles, less than 1-2 nm in diameter, can readily flow from a healthy circulatory system and harm healthy cells. The kidneys quickly filter substances that are less than 10 nanometres in diameter.[22].

One of the most cutting-edge technologies in nanoparticle applications is drug design at the nanoscale, which has been the subject of much research. The ability to change properties including solubility, drug release pattern, and immunogenicity is one of the approach' numerous potential advantage. As such, it may result in a longer drug lifespan, better and more convenient methods of administration, decreased toxicity, fewer adverse effects, and superior biodistribution [23].

The capacity of nano-carriers to specifically target cancer cells increases treatment efficacy while shielding healthy cells from harm, making them an essential part of drug delivery systems. A serum glycoprotein called transferrin is essential for delivering iron to cells. The highest of solid tumor cells often express transferrin receptors excessively, while typical cells have lower levels of these receptors. Transferrin-conjugated nanoparticles are employed as an active targeting method to deliver drugs for the treatment of cancer. [24, 25].

Drug delivery methods based on nanoparticles provide a number of benefits, such as improved stability, biocompatibility, tumor targeting, and pharmacokinetics. They also have a major impact on overcoming medication resistance and lowering systemic toxicity. These benefits allow for the widespread use of drugs based on nanoparticles in a range of treatment modalities, such as radiation, targeted therapy, chemotherapy, gene therapy, and hyperthermia.

2.2. Nanoclusters

Building hierarchical structures in the shape of nanoclusters is the subject of one of the most promising treatments. In the presence of biomolecules, this technique prepares individual building blocks without using hazardous chemicals. Nanoclusters for cancer treatment can be made from a variety of building elements. The hunt for nanocarriers with decreased toxicity, enhanced biocompatibility, and enhanced biological distribution has received more attention, particularly when it comes to biodegradable materials and inorganic nanoparticles [26].

Nanoclusters have attracted considerable interest from researchers in the biomedical field because of their unique properties. When designing nanoclusters for cancer treatment, it is important to carefully consider their size, charge, and surface characteristics to ensure optimal biodistribution in patients. [27].

Nanosystems consisting of a few to a hundred atoms are known as metallic nanoclusters (MNCs). Since their size (less than 2 nm) is similar to the electrons' Fermi wavelength (about 0.7 nm), they behave like molecules [28]. For biological uses in biolabeling and bioimaging, MNCs made of Au and Ag have been thoroughly researched [29]. With the help of metal cores and surface ligands, metallic nanoclusters offer a superb, adaptable, and multipurpose substrate for the self-assembly of colloidal superstructures. Applications for these structures include medication administration, treatment, and bioimaging.

It would be very beneficial to be able to create materials separately without having to handle hazardous chemicals or manipulate proteins into big hierarchical nanostructures (like nanoclusters). Creating these nanoclusters from a variety of materials with distinct physicochemical characteristics and functions could greatly improve cancer treatment. The creation of multi-component nanoclusters that combine several functions, including anti-cytotoxic activity, bioimaging targeting, and therapy drug administration, is still in its infancy as a cancer theranostics technique.

There is great potential for enhancing cancer treatment through the practical application of nanomaterials. As a result, this field of research will likely yield significant breakthroughs and results in the coming years. The various biological applications of nanomaterials are presented in Table 1.

Table 1: Different Biomedical Applications of Nanomaterials

Name of Nanomaterials	Applications	Description	References
Nanoparticle	Food packaging, wastewater treatment, Cancer therapy	Additionally,nanoparticles can actively circumvent cancer cells' drug-resistant defenses, enabling medications to reach their intended sites and have therapeutic effects.	[30]
Nanocluster	Antibacterial Activity, Hyper therthemia treatment, drug delivery	For drug transport and therapy, multifunctional tiny clusters have been utilized, which is particularly useful for biomedical treatment and diagnosis.	[31]
Nanorods	Nanocapacitors for photothermal treatment, drug delivery, bioimaging, etc.	Although they lack interior surfaces, nanorods resemble nanotubes. Heat-stable but less adaptable than nanotubes Produced: metal, metal oxide, and carbon	[32]
Nanowire	Magnetic devices, nanowire batteries, nanogenerators, semiconductors, etc.	Although their lengths are not limited, nanowires usually have diameters of a few tens of nm. Made of metal oxide, ceramic, and metal	[33]
Nanotube	Drug Delivery, Targeted Drug Delivery	Multi-walled carbon nanotubes have been used as medicinal carriers because of their increased capacities of loading the drugs and controlled patterns of release.	[34]

2.3. Nanorods

Fundamental and applied research is being conducted on nanorods, which are nanostructures. A nanorod's typical length ranges from 10 to 120nm. Many varieties of nanorods have been thoroughly investigated, including magnetic, ZnO, gold, and carbon nanorods. Some methods have been put up to create these nanorods. Carbon nanorods have attracted a lot of attention in recent decades due to their physical properties (such as particle shape, size, large surface area, and improved pore size distribution) [35].

By adding different functional groups to their pore surfaces, carbon nanorods show enhanced physicochemical characteristics. Gold nanostructures, like other conventional nanomaterials, have garnered significant interest and developed into crucial platforms in nanobiotechnology and nanomedicine. [36]. The optical characteristics of gold nanoparticles, which are greatly impacted by their size, aspect ratio, and shape, are what make them significant in medicine [37].

Gold nanoparticles are becoming more and more popular in medical applications because of their special optical qualities, simplicity of functionalization, and good biocompatibility [38]. They have the potential to be used as carriers for gene delivery [40], antigen delivery in immunization [39], and other therapeutic targets [41].

Gold nanorods (GNRs) are promising nanocarriers for the targeted delivery of therapeutic cargo since they can be functionalized and concurrently loaded with genes or medications. Low toxicity is a crucial property of materials employed in medication delivery systems.

2.4. Nanotubes

Nanotubes come in diverse shapes, including closed, spiral multi-walled, short, open, various double-walled, long, single-walled, and various spiral configurations. These hollow cylindrical carbon molecules have unique properties that make them ideal for a variety of applications in nanotechnology, electronics, and optics. [42].

A thick sheet of graphene is rolled into a smooth cylinder with a diameter of about one nanometer (nm) to create them. High mechanical strength, a wide range of electrical characteristics, a huge surface area, low weight, chemical resilience, and superior thermal stability are all attributes of carbon nanotubes [43].

Current cancer treatments, including radiation therapy, chemotherapy, and surgery, often harm healthy cells. [44].

In the investigations of in vivo and in vitro studies, *f-CNTs* have demonstrated better targeting capabilities and biocompatibility, yielding encouraging findings.

The prospective uses of carbon nanotubes in cancer treatment, such as imaging, drug delivery, and combination therapy, have garnered a lot of scientific attention in the past ten years. The creation of new medical instruments and equipment has greatly assisted scientific progress. Together with their exceptional capacity to form bonds with other materials, carbon nanotubes (CNTs') diverse mechanical, physical, and chemical characteristics enable a broad range of medical uses.

3. THERANOSTICS

The creation of customized drug delivery systems using nanoparticles is a significant advancement in the therapeutic application of these microscopic materials. By utilizing the special qualities of nanoparticles at the nanoscale, this novel strategy seeks to improve the precision and efficacy of drug delivery [45]. By greatly enhancing the solubility, stability, and bioavailability of medications that are poorly soluble in water, engineered nanoparticles can overcome the fundamental drawbacks of traditional therapeutic formulations [46].

The specificity of drug delivery systems is increased when targeting ligands are included in nanoparticles [figure 3]. Furthermore, prolonged and sustained medication release at the target region is the outcome of nanoparticles' release characteristics. In addition to improving treatment outcomes and possibly lowering the frequency of drug administration, this controlled-release profile guarantees that medications maintain a therapeutic concentration for an extended length of time.

In the treatment of chronic illnesses, where regular therapeutic dosages are essential, this aspect is very helpful [47].

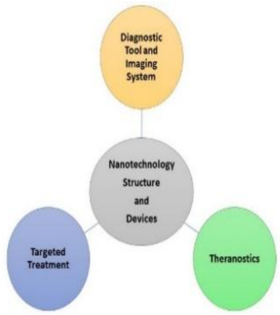

Fig.3. Targets and goals of nanomedicine in healthcare research

4. CONCLUSION

The growing need for more potent and specialized treatment options is predicted to fuel a sharp increase in the use of nanotechnology in healthcare over the next several years. With its capacity to lessen the side effects of traditional medications, nanomedicine has enormous potential to revolutionize the way that many chronic illnesses are treated. The promise of nanoparticles in drug-targeted delivery is demonstrated in this work, which also demonstrates how they can assist innovative therapeutic approaches, including photothermal therapy and controlled drug release, improve targeted drug delivery, and enable sophisticated imaging techniques. The investigation of nanoparticles for drug delivery systems shows how they can be used to get around the drawbacks of conventional pharmaceutical treatments. Nanoparticles can be engineered to target particular disease locations, enhance bioavailability, and reduce systemic adverse effects by utilizing their unique biological and physical characteristics. This study emphasizes how crucial nanomaterials are becoming to the design and development of next-generation drug delivery systems, which will enhance treatment effectiveness and give patients more individualized care.

Furthermore, as these interactions are essential to maximizing therapeutic results, the results of this study highlight the necessity of future research into the interactions between nanoparticles and biological systems. Future developments in nanotechnology, especially in medication delivery systems, could completely transform the way complicated illnesses like cancer, heart disease, neurological disorders, and infectious diseases are treated. In the end, the ongoing advancement and improvement of nanomaterials for drug delivery will open the door to safer, more accurate, and more successful treatments, giving patients everywhere new hope.

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