NANOTECHNOLOGY IN MODERN MEDICINE: THERAPEUTIC INNOVATIONS AND APPLICATIONS

Abstract

Nanotechnology has ushered in a novel age of medical advancement. Nanotechnology employs principles from physics, chemistry, biology, and engineering to manipulate nanoscale materials to create novel medical instruments for diagnosis, treatment, and monitoring. This abstract provides a concise overview of the contributions of nanotechnology to modern medicine, focusing on the advancements in therapy and their practical implementation. The field of nanotechnology has enhanced the process of administering drugs. Liposomes, micelles, and nanoparticles are vehicles that enable precise drug delivery. Improving accuracy enhances therapy's effectiveness and diminishes adverse effects, thus addressing a persistent issue in pharmaceutical administration. Nanocarriers can surmount biological obstacles, penetrate tissues, and accumulate in areas affected by illness, enhancing the efficacy of cancer and infectious disease therapies. Nanotechnology has significantly improved the fields of imaging and diagnostics. Nanoparticles engineered with imaging agents may accurately observe minuscule characteristics, facilitating the early detection of illnesses. Quantum dots, gold, and magnetic nanoparticles accurately visualize cellular and molecular processes. These little imaging instruments enable medical professionals to identify early medical conditions swiftly and precisely. Nanotechnology is crucial in advancing regenerative medicine by facilitating tissue formation and repair. Scaffolds and nanoparticles imitate the extracellular matrix, promoting cell proliferation and tissue regeneration. These developments have significant implications for medical

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conditions that necessitate organ transplants or tissue repair, offering a solution to the limitations of conventional transplantation techniques. Nanosensors incorporated into medical equipment can detect physiological signs at the molecular level. It impacts customized medicine, as treatment strategies may be modified according to individual reactions. Nanotechnology-based sensors integrated into wearable devices enable the continuous and non-intrusive monitoring of health indicators for health surveillance purposes. In summary, nanotechnology has significantly transformed medicine through several medical breakthroughs and tangible implementations. Nanotechnology impacts medication's precise administration, medical image visualization, and regenerative medicine development. It has the potential to revolutionize medical treatments by enhancing precision, effectiveness, and customization for individual patients.

Keywords: Nanotechnology, Visualization, Liposomes

I. INTRODUCTION

1. What Exactly is Nanotechnology?

The prefix "nano" is widely recognized in academic circles as denoting a unit of measurement equivalent to one-billionth of a meter, or 10-9 meters, and is conventionally abbreviated as "nm." The nanometer, equivalent to one billionth of a meter, is of such minuscule dimensions that it eludes direct observation by the unaided human eye or conventional light microscopy. As an illustration, it can be observed that the thickness of a sheet of paper is approximately 100,000 nanometers. In contrast, the diameter of a single gold atom measures roughly one-third of a nanometer. "nanoscale" refers to dimensions ranging from 1 to 100 nanometers.[1]

The utilization of materials at the nanoscale in the field of nanotechnology represents a relatively recent and burgeoning area of study for researchers. This domain exhibits a notable surge in commercially viable applications, which exhibit the potential to yield significant technological advancements aimed at safeguarding the environment and benefiting humanity. Various fields, including medicine, textiles, environmental remediation, and computer chip manufacturing, currently utilize these technologies in novel and captivating applications.[2-5]

Moreover, it is worth noting that nanoscience and nanotechnology are not novel concepts within scientific inquiry. Over the last five decades, there has been a notable proliferation in the field of immunology, which has given rise to many novel challenges. The continuous advancements in scientific research have propelled scholars into the realm of molecular biology and genomics, which encompass the fields of micro-science and microtechnology. Presently, nanotechnology primarily concentrates on materials with dimensions ranging from 1 to 100 nanometers. At these particular dimensions, advancements in materials have emerged that aid researchers in effectively managing the accuracy and precision of utilizing novel nanomaterials.[6-8] Similarly, utilizing nano-sized particles allows for exploring distinct phenomena that are not attainable when working with bulk materials containing molecules or individual atoms.[6-8] Nanotechnologies have changed the game in almost every industry and aspect of society. They give us way more excellent, safer, longer-lasting, and more innovative stuff for medicine, communications, everyday life, agriculture, and all that good stuff.[9]

In general, there are two kinds of ways that nanoparticles are used in everyday items. First, nanomaterials can be combined with or added to an already-made product to make it work better by giving it unique qualities. If not, nanomaterials like nanocrystals and nanoparticles can be used directly to make high-tech and powerful gadgets because of how they are made. The advantages of nanomaterials could affect the future of almost every industry.[10]

Nanomaterials have demonstrated advantageous applications in everyday items, including sunscreens, cosmetics, sporting goods, tires, electronics, and numerous other products.[11] Furthermore, nanotechnology has brought about significant advancements in the realm of medicine, particularly in diagnostic techniques, imaging technologies, and drug administration. Now a day’s, nanotechnology has exerted a notable influence in the area of the healthcare system.[12]

Nanomaterials facilitate the large-scale production of products that exhibit improved functionality, substantially reduced costs, and more environmentally sustainable manufacturing processes, enhancing healthcare and mitigating the environmental consequences of manufacturing.[13]

2. Historical Background and Evolution of Nanotechnology

Nanotechnology encompasses diverse technologies operating at the nanoscale, incorporating various chemical, physical, and biological processes.[14,15] The precise timeframe for the inception of nanotechnology development is evidenced by its historical roots, wherein individuals unknowingly utilized nanoscale materials in the distant past.[16]

The term "nanotechnology" was initially coined by Norio Taniguchi during the International Conference on Industrial Production held in Tokyo in 1974. Taniguchi employed this term to elucidate the precise manipulation of materials at the nanometer scale and the development of nano-sized mechanisms. The concepts of the nanotechnological approach were initially proposed by Richard Feynman, widely recognized as the Father of Nanotechnology, during his lecture at the American Physical Society in 1959. Eric Drexler expanded these ideas further in 1986.[14]

The domain of nanotechnology and nanoscience witnessed notable progressions during the initial years of the 1980s, primarily attributed to two pivotal advancements: the rise of cluster science and the creation of the Scanning Tunneling Microscope (STM) in 1981. The discovery of Fullerenes in 1985, followed by Japanese scientists' improvements in Carbon Nanotubes in 1991, can be linked to these key discoveries. A considerable number of major discoveries were made during the mid-1980s and the early 1990s that had a vital effect on the following advancement of nanotechnology. The United States began its first nanotechnology programme in 1991, with funding from the National Science Foundation. Following that, the United States' National Nanotechnological Initiative (NNI) got formal approval in 2001. Subsequently, numerous advancements in technical research and the establishment of scientific departments have occurred globally, with notable concentrations in countries including England, Japan, China, Germany, France, South Korea, and, more recently, in the CIS countries.[14-16]

The emergence of nanotechnology can be traced back to the 1960s, with significant advancements occurring in the 1980s and 1990s, marking the beginning of its independent development. Based on the recommendations the U.S. National Research Council (NRC) put forth regarding toxicity testing in the 21st century, high-throughput screening for nanomaterials shows considerable promise and holds potential for future implementation. Despite the inherent complexity of nanomaterials, which poses challenges in conducting safety assessments, the prospects of nanotechnology appear promising.[17]

II. NANOTECHNOLOGY IN MEDICINE AND HEALTH CARE

Nanomedicine is a term for nanotechnologies used in medicine and health care. Nanomedicine, in particular, uses technologies at the nanoscale and methods that can be used with nanotechnology to prevent, identify, track, and treat diseases.[18] Nanotechnologies, such as imaging techniques and diagnostic tools, drug delivery systems, tissue-engineered constructions, implants, and pharmacological treatments, offer enormous promise in medicine.[19] They have also enhanced therapy for a wide range of ailments, including cardiovascular disease, cancer, musculoskeletal disorders, mental and neurological disorders, bacterial and viral infections, and diabetes.[20]

1. **Nanosystems:** Numerous nanoparticles and nanomaterials have been thoroughly researched and shown to have a favourable safety profile for medicinal uses. This section will give an overview of many commonly used kinds of nanoparticles in figure 1 [21]

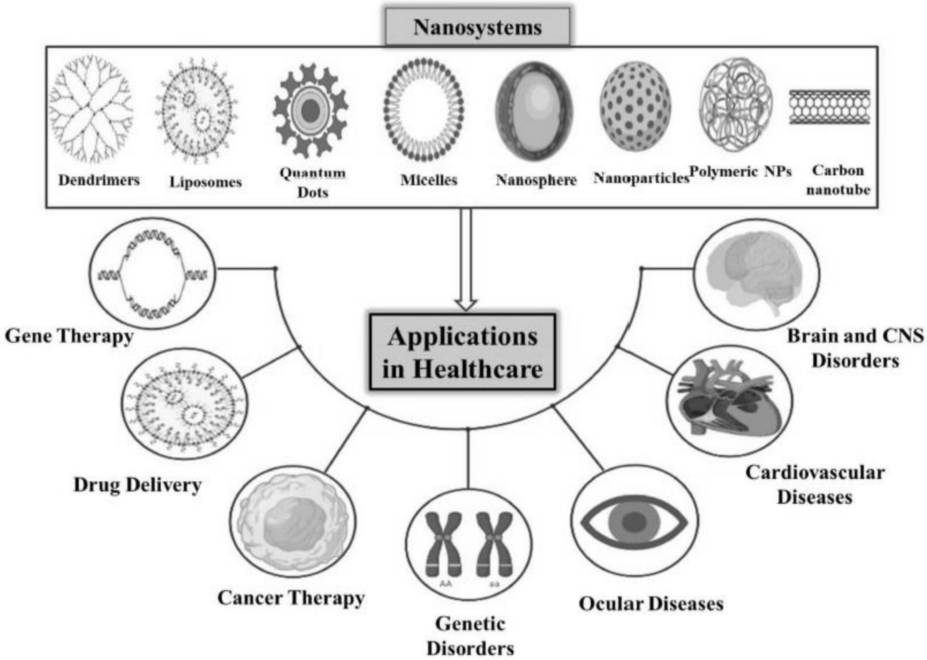

Figure 1: Applications of Diverse Nanosystem in allied Healthcare Domains are presented Schematically

- **Micelles:** Micelles are amphiphilic surfactant molecules made up of lipids and other amphiphilic chemicals. Micelles can successfully integrate hydrophobic medicinal substances because of their natural proclivity to spontaneously aggregate and self-assemble into spherical vesicles when exposed to water environments. The micelles have an exterior monolayer with hydrophilic characteristics and a core with hydrophobic qualities. Micelles have special properties that allow them to improve the solubility of hydrophobic medicinal substances, resulting in increased bioavailability. Micelles come in a variety of sizes ranging from 10 to 100 nanometers in diameter. Micelles are widely used in a variety of applications such as drug administration, imaging, contrast agents, and therapeutic agents.[22]

- **Liposomes:** Liposomes are spherical vesicles characterised by the presence of lipid bilayers, with particle sizes ranging from 30 nanometers to several microns. Hydrophilic therapeutic drugs can be encapsulated inside the aqueous core of liposomes, whereas hydrophobic medicines can be encapsulated within the lipid bilayer. Liposomes are very adaptable since their surface characteristics may be adjusted by introducing polymers, antibodies, and proteins. This modification incorporates macromolecular pharmaceuticals into the liposomal structure, such as nucleic acids and crystalline metals. Poly Ethylene Glycol (PEG) liposomal doxorubicin, commercially known as Doxil, represents the pioneering nanomedicine that has received approval from the U.S. Food and Drug Administration (FDA). This nanomedicine has been successfully employed in managing breast cancer, as it effectively increases the concentration of the drug in malignant effusions without necessitating an escalation in the total dosage.[21-22]

- **Dendrimers:** Dendrimers are a macromolecule characterized by their branched repeating units emanating from a central core. These structures are composed of exterior functional groups.[22,23-24] The functional groups present in a compound can exhibit anionic, neutral, or cationic characteristics, thereby allowing for modifications to the overall structure and the compound's chemical and physical properties. Dendrimers can encapsulate therapeutic agents within their internal cavities or bind them to their surface functional groups, thereby conferring a notable degree of bioavailability and biodegradability upon dendrimers. Previous studies have demonstrated that the conjugation of dendrimers with saccharides or peptides results in heightened antimicrobial, anti-prion, and antiviral properties and enhanced solubility and stability when therapeutic drugs are absorbed.[26] The utilization of polyamidoamine dendrimer-DNA complexes, also known as dendriplexes, has been the subject of research for their potential as gene delivery vectors. These complexes show potential in enabling sequential gene expression, targeted drug delivery, and enhancing drug effectiveness.[23,24] Due to their inherent transformability, dendrimers exhibit considerable potential as particulate systems in biomedical applications, particularly imaging and drug delivery.[27-28]

- **Carbon Nanotubes:** (CNTs) are cylindrical structures composed of carbon atoms arranged in a hexagonal lattice. They possess unique physical Carbon nanotubes, cylindrical structures composed of graphene, a single layer of carbon atoms that have been rolled up. Nanotubes can exist in two primary forms: single-walled or multi-walled. Additionally, they can also be comprised of multiple concentrically interlinked nanotubes.[29] Carbon nanotubes possess a significantly elevated loading capacity as drug carriers due to their substantial external surface area. Moreover, carbon tubes' distinctive optical, mechanical, and electronic characteristics have made them attractive for applications as imaging contrast agents [30-31] and biological sensors.[32]

- **Metallic Nanoparticles:** Metallic nanoparticles are tiny particles of metal atoms that exhibit unique physical and chemical properties due to their nanoscale dimensions. These Metallic nanoparticles encompass a variety of nanoparticles, such as iron oxide and gold nanoparticles. Iron oxide nanoparticles are composed of a magnetic core with a diameter ranging from 4 to 5 nanometers, surrounded by hydrophilic polymers such as dextran or PEG, with a size of 17 to 20 nanometers. In contrast, gold nanoparticles comprise a central gold atom enclosed by reactive groups with negative charges on the outer layer. As evidenced by previous studies, these surface groups can be modified by attaching a single layer of ligands to enable active targeting.[28-31].

Metallic nanoparticles have been employed as contrast agents for imaging purposes [32], utilized in laser-based therapeutic interventions, as optical biosensors, and as carriers for drug delivery.[33]

- **Quantum Dots**: Quantum dots are nanoscale semiconductor particles that exhibit unique optical and electronic properties due to quantum confinement effects. Quantum dots (Q.D.s) are fluorescent semiconductor nanocrystals with sizes ranging from 1 to 100 nm. They have demonstrated promising capabilities for various biomedical purposes, including drug delivery and cellular imaging.[28,34-35] Quantum dots exhibit a shell-core architecture, wherein the core structure commonly comprises elements from the periodic table's II-VI or III-V groups. Quantum dots have been utilized in medical imaging due to their unique optical characteristics and dimensions, encompassing high luminosity and durability.[21,34]

2. **Application of Nanotechnology in Medical Sciences:** Nanotechnology helps with various diagnostic procedures, drug delivery, sunscreens, antibacterial wraps, fungicides, and procedures for warm production techniques. They are also being studied in the agricultural industry for possible uses in visualizing fungicides, anticancer agents, and biomedical applications.[35] Nanomaterials are likewise insinuated as "a miracle of present-day medication".[36] Nanomaterials have been investigated for various biomedical uses, including anticancer, antidiabetic, antibacterial, antifungal, soothing, and general drug transport applications.[37]

   Nanodevices and Nanopharmaceuticals are significant new fields of technology. Nanotechnology expands research and applications by interacting with the nanometer class of biomolecules. The interaction between biomolecules and nanodevices can be understood in vitro and in vivo. Nanomedicine is the utility of nanotechnology within the fields of fitness and medicine. The area of clinical nanoscience has many predictable advantages and can gain all humankind. With the early detection and prevention of nanomedicine, ailment diagnosis, suitable remedy, and tracking may be improved. Nanotechnology may be used to copy or restore broken tissues.

   Nanoparticles uses in Various Ways

   - **Use in Drug Delivery:** Nanotechnology-based drug delivery relies on three factors:

     - Effective drug encapsulation and
     - The drugs are successfully transmitted to the target area of the body.
     - The drug is usually released to that area.

     The side effects of the drug are greatly minimized because the active substance is deposited in the disease zone only for this region, and a wide range of nanoparticles are delivered from the small molecule drug to the targeted area. Nanosponges are essential tools in drug delivery.[38] They can improve the bioavailability of drugs due to their small size and porosity. They can be designed to deliver drugs to specific sites, which helps prevent the breakdown of drugs and can prolong drug release in a controlled manner.

- **Nanotechnology-Based Applications in Cancer-Targeted Therapy:** Because of their nano size, nanoparticles can be used in body scans. Quantum dots with other limiting properties can produce large images of tumours. Nanoparticles are brighter than organic dyes and require a light source to generate excitement. In cancer photodynamic therapy, nanoparticles are introduced into tumours in the body and irradiated with light seen from the outside. Nanoparticle particles absorb light and, in the case made up of metals, N.P.s heated with light energy. A high-energy oxygen molecule chemically reacts with malignant cells and destroys them without reacting with other cells in the body. As a non-invasive treatment for tumours, it has become beneficial. The applications of many nanosystems in the treatment of cancer [38] are summarized as follows:

  - **Carbon Nanotubes,** with a diameter of 0.5 to 3 nanometers and a length of 20 to 1000 nanometers, are used to detect DNA mutations and identify disease-causing protein biomarkers.
  - **Dendrimer:** Dendrimers are smaller than 10 nm and can be used in contrast media as controlled release drug administration.
  - **Nanocrystal:** Nanocrystal with a size of 2 to 9.5 nm improve the formulation of poorly dispersible drugs by surface-coating.Nanoparticles have a size of 10-1000 nm. They are used as contrast agents for MRI and ultrasound imaging and target drug delivery, as well as permeation activators and cell self-destruct reporters that form circuits.
  - **Nanoshells:** Nanoshells are used for tumour-specific imaging and thermal ablation of deep tissue.
  - **Nanowires:** Nanowires are used for tumour shaping and thermal ablation of deep tissues. Nanowires can be used to detect DNA mutations and gene expression biomarkers.
  - **Quantum Dots:** Quantum dots ranging in size from 2 to 9.5 nm can be used for the optical detection of genes and proteins in animal models, cell analysis, and imaging of tumours and lymph nodes.

The efficacy of anticancer therapies is commonly assessed based on their ability to reach the intended target site while minimizing adverse effects selectively. Implementing chemical alterations on nanoparticle carriers' surfaces can potentially enhance the efficacy of targeted delivery. Incorporating PEG or polyethylene oxide is widely regarded as one of the nanoparticle's most notable surface modifications. These modifications increase the specificity of drug uptake and improve the ability to target tumours. The utilization of polyethylene glycol (PEG) evades the immune system's recognition of nanoparticles as exogenous entities, thereby enabling their circulation within the bloodstream until they reach the tumour site.

Moreover, the utilization of hydrogel in the context of breast cancer is a prominent illustration of this cutting-edge technology. Herceptin, a monoclonal antibody, treats breast cancer by targeting the human epidermal growth factor receptor 2 (HER2) in malignant cells. A hydrogel containing vitamin E has been developed to enable sustained release of Herceptin at the intended location over an extended period following a single administration. The enhanced retention of Herceptin within the tumour, facilitated by hydrogel-based drug delivery, demonstrates superior efficiency compared to conventional subcutaneous and intravenous delivery methods. Consequently, hydrogel-based delivery proves to be a more effective anti-tumour agent.[39-41] Nanoparticles possess the capacity to undergo various modifications that can effectively extend their circulation time, optimize drug localization, augment drug effectiveness, and potentially mitigate the emergence of multidrug resistance, all by leveraging the capabilities offered by nanotechnologies.

Multiple studies have employed FDA-approved nano drugs, such as Abraxane®, Doxil®, or Genexol-PM®, as adjuncts in combination cancer therapy. The approval of Abraxane®, a nanoparticle formulation of paclitaxel stabilized by albumin (nab-paclitaxel), has been granted for the therapeutic management of metastatic breast cancer.[42] As of August 2020, Clinicaltrials.gov reported that over 900 ongoing clinical trials are investigating the efficacy of nab-paclitaxel as an anticancer agent. Furthermore, the utilization of nab-paclitaxel, in conjunction with 5-chloro-2.4-dihydrooxypyridine, tegafur, and uracil potassium, has demonstrated encouraging outcomes in the management of breast cancer patients who do not express the HER2 protein.[43] Doxorubicin, daunorubicin, paclitaxel, and vincristine have been extensively studied as anticancer agents in liposome-based drug formulations.[21,22] Table V presents a compilation of nanomedicines that have obtained approval from the Food and Drug Administration (FDA). [21]

Clinical Agents	Formulation	Applications
Eligard	Leuprolide acetate and polymer [poly (DL-lactide-co-glycolide)]	Prostate cancer
Genexol-PM Doxil/Caelyx	mPEG-PLA micelle loaded with paclitaxel Liposomal doxorubicin	Metastatic breast cancer Ovarian, breast cancer, Kaposi's sarcoma, multiple myeloma
Myocet	Liposomal doxorubicin	Combination therapy with cyclophosphamide in metastatic breast cancer
Onivyde	Liposomal irinotecan	Pancreatic cancer
Cynviloq	Paclitaxel-loaded poly(ethylene glycol)-b-poly(D,L-lactic acid) block copolymers	Non-small cell lung cancer and metastatic breast cancer
Nanoxel	Docetaxel-loaded poly(ethylene glycol)-b-poly(D,L-lactic acid) block copolymers	Breast cancer, non-small-cell lung cancer, prostate cancer, ovarian cancer, head and neck cancer, oesophageal cancer

- **In the Treatment of Neurodegenerative Disorders:** Perhaps the main utilizations of nanotechnology are the treatment of neurodegenerative illnesses.[45] Different nanocarriers for the treatment of the focal sensory system have been examined, like dendrimers, nano gels, nanoemulsions, liposomes, polymer nanoparticles, nano lipid solid particles, and nanostructures. The conveyance of these nano-drugs has been finished utilizing a few Blood-Brain Barrier models with endocytosis and, additionally, transcytosis and is used in the treatment of focal sensory system sicknesses (like Alzheimer's infection, cerebrum growths, encephalopathy, HIV and Acute ischemic stroke) made early preclinical progress conceivable. Nanomedicine can be improved by further developing BBB penetrability and lessening neurotoxicity.

- **In the treatment of Tuberculosis:** Tuberculosis (T.B.) is a fatal infection. Long-term treatment and medication can lead to the development of multidrug-resistant bacteria and affect the patient's lifestyle. The development of new antibiotics could overcome drug resistance. Nanotechnology is one of the most promising ways to develop more robust and effective drugs. This can lead to the developing of anti-tuberculosis drugs that are more effective and cheaper than anti-tuberculosis drugs.[44]

- **Modified Medicated Textiles:** With the help of nanotechnology, a new type of antibacterial cotton quilt was developed to make antibacterial fabrics. The development of nanotechnology has developed new modified antibacterial substances. The use of existing antibacterial agents in the fabric has been reported. It has a well-structured antibacterial activity and has improved methods, emphasizing nano-inorganic substances and their application to fabrics. [45]

- **Tissue Engineering:** Tissue Engineering can be used to repair or regenerate damaged tissue. Using appropriate nanomaterials and growth factors, artificially stimulated cell proliferation, organ transplantation, and a framework based on artificial transplantation can extend lifespan. It could be.[45]

- **Nanopharmaceuticals:** Nanomedicine can distinguish sicknesses at a prior stage, and analytic applications can be based on traditional nanoparticle technology. Nanomedicine is a new field where drug particle size or therapeutic delivery systems operate on the nanometer scale. The dosage of specific active ingredients for particular disease sites is still a challenge for the pharmaceutical industry. Nanomedicine has excellent potential to solve this shortcoming of traditional therapy that provides site-specific drug targets. Nanomedicine can decrease fundamental poisonous incidental effects, in this manner improving patient compliance.[44]

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