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Review Article

A Review on Nano-Medicine

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ABSTRACT

Nanomedicine has emerged as a transformative field at the intersection of nanotechnology and medical science, operating at the molecular scale to revolutionize healthcare delivery. The integration of engineered nanostructures with biological systems has enabled precise drug delivery mechanisms, enhanced diagnostic capabilities, and innovative therapeutic approaches. Sophisticated nanocarriers and smart materials have demonstrated remarkable success in targeted drug delivery, particularly in cancer treatment, where they effectively overcome biological barriers while minimizing systemic toxicity. Advanced nanoplateforms have facilitated real-time disease monitoring, early detection of biomarkers, and personalized therapeutic interventions. The ability to manipulate magnetic nanoparticles with external magnetic fields and their compatibility with biological systems make them versatile tools in the field of nanomedicine. Recently, the integration of various nanotechnologies with biomedical science, pharmacology, and clinical practice has led to the emergence of the discipline of nanomedicine. Owing to the special qualities of nanoparticles and related nanostructures, their uses in controlled drug and gene delivery, imaging, medical diagnostics, monitoring therapeutic outcomes, and support ing medical interventions offer a fresh approach to difficult problems in difficult areas like the treatment of cancer or crippling neurological diseases. The potential for multi-functionality and advanced targeting tactics in nanoparticle products exists. It may maximize the effective ness of current anticancer drugs by enhancing the pharmacodynamic and pharmacokinetic characteristics of conventional therapies. These nanometer-sized substances' distinctive electrical, magnetic, and optical characteristics have opened up a wide range of biological uses. As they may be used in healthcare situations due to their bioactivity, iron-oxide-based magnetic nanoparticles, in particular, have been shown to be incredibly useful deep-tissue scanning tools.

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The limitations of nanomedicines in targeted drug delivery, such as limited drug payload capacity and lack of specificity, must also be addressed. Despite the challenges, the prospects for nanomedicine are promising, with the potential to revolutionize personalized medicine, improve disease diagnosis and treatment, and support tissue regeneration and repair. Integration with artificial intelligence can lead to more precise and efficient drug delivery and disease diagnosis. Continued investment and collaboration between researchers, healthcare providers, and industry partners can help overcome obstacles and unlock the full potential of nanomedicine. Overall, nanomedicine is an exciting and promising field that has the potential to significantly improve healthcare outcomes.

INTRODUCTION

Operating at a scale where the basic characteristics of materials interact with biological processes, nanomedicine represents a paradigm leap in healthcare. Materials have special physicochemical characteristics at the nanoscale (1–100 nanometers) that can be used for medical and diagnostic applications [1]. The field was created when molecular biology, nanotechnology, and medical research came together, providing previously unheard-of chances to solve persistent problems in healthcare delivery [2]. The urgent demand for more accurate, efficient, and customized therapeutic techniques has propelled the development of nanomedicine. Poor medication solubility, insufficient tissue distribution, and serious adverse effects are common problems with traditional medical therapies. Through cutting-edge methods for medication delivery, illness diagnosis, and therapeutic intervention, nanomedicine tackles these issues [3]. Targeted drug delivery systems that minimize side effects while maximizing therapeutic efficacy, sophisticated diagnostic tools that can identify diseases at the molecular level, and regenerative medicine techniques that encourage tissue repair and regeneration are just a few of the major areas in which the use of nanotechnology in medicine has revolutionized

[4]. In cancer, where nanoparticle-based therapies have shown better tumor targeting and lower systemic toxicity as compared to traditional chemotherapy, these developments have had a particularly significant impact [5]. The use of nanoparticles for illness detection, monitoring, control, prevention, and therapy is known as "nanomedicine," which refers to the application of nanotechnology for medical purposes [6]. However, different scientific and international regulatory organizations have disagreed on what constitutes a nanomaterial. Because of their small size, nanomaterials have unique physicochemical features that differ from those of their traditional bulk chemical equivalents. As a result, some efforts have been undertaken to develop a consensus definition. These characteristics significantly expand a number of medication research opportunities, however some safety concerns have surfaced. Concerns regarding the use of nanomaterials include the physicochemical characteristics of the nano-formulation that may change pharmacokinetics, including absorption, distribution, elimination, and metabolism; the possibility of more easily overcoming biological barriers; toxic characteristics; and their persistence in the environment and human body. [7-6] Nanomedical research is advancing quickly and is greatly aided by funding and public policies. [8,9] Numerous advantages, such as enhanced efficacy, bioavailability, dose-response, targeting capability, customisation, and safety in comparison to conventional medications, could result from the ongoing development of nanomedicines. [9–12]. The creation of multifunctional nanoparticle (NP) complexes that may concurrently deliver therapeutic and diagnostic substances to specified areas may be the most intriguing idea in nano-medical research. [12, 13] These capabilities are unparalleled and mark a significant advancement in the diagnosis, treatment, and follow-up of patients. [13]



Nevertheless, despite these possible advantages, crucial information about the pharmacokinetics, pharmacodynamics, and toxicity of several nanomaterials is presently unavailable. [12–14]

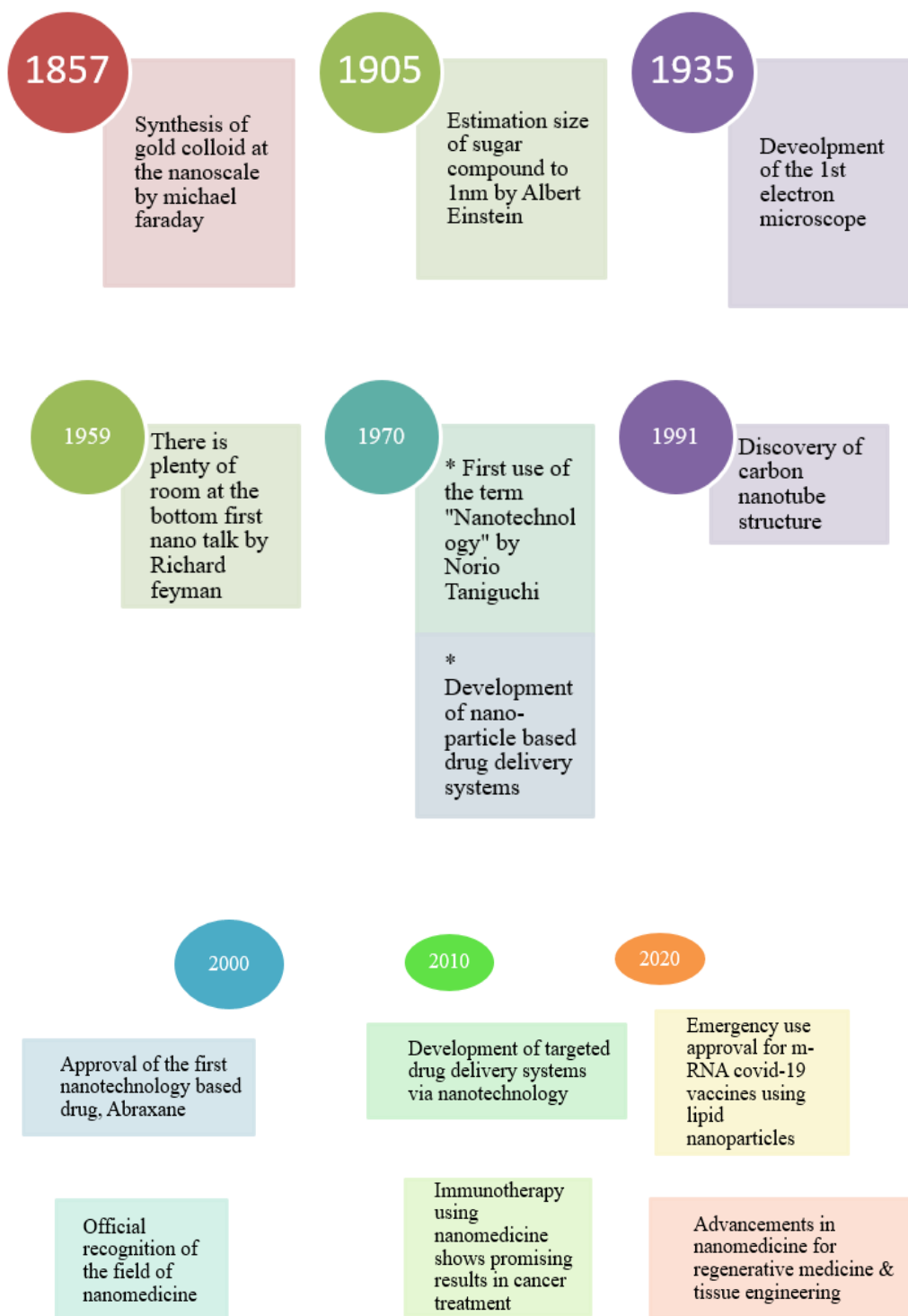


Fig.1. Historical landmarks in the evolution from nanotechnology to nanomedicine. “Created with BioRender.com.”.

What Is Nanotechnology?

The fast developing science of nanotechnology is predicted to have a transformative effect on numerous industries, including healthcare. [8,9] Numerous scientific disciplines, including chemistry, biology, physics, mathematics, and engineering, have come together to enable nanotechnology. [8, 9, 15]. The prefix "nano-" is derived from the Greek word for "dwarf," and a nanometer (nm) is one billionth of a meter. [11, 16] Atoms, molecules, and submicroscopic objects—which typically range in size from 1 to 100 nm—can be investigated, manipulated, and controlled using new technologies made possible by nanotechnology. [8–13] Scientists can benefit from naturally existing quantum effects at the nanoscale level that affect biological, physical, chemical, mechanical, and optical features thanks to nanotechnology. [13, 16, 17] Because of these special effects, nanoscale materials frequently have desirable chemical, physical, and biological features that set them apart from their bigger, or "bulk," counterparts. [18]

What Is Nanomedicine?

The multidisciplinary field of nanomedicine is the result of the intersection of nanotechnology and medicine. [13] This emerging discipline, which studies physiological processes at the nanoscale level, has benefited from developments in genetics, proteomics, molecular and cellular biology, material science, and bioengineering. [13, 15] Since the size of many biologically significant molecules, including water, glucose, antibodies, proteins, enzymes, receptors, and hemoglobin, are already within the nanoscale range, many of a cell's internal operations naturally take place at the nanoscale level. [13, 17] Nanotechnology is currently being used by numerous researchers to improve efficacy, safety, sensitivity, and personalization in medical treatments, equipment,

and instruments. [17] Improved bioavailability, decreased toxicity, increased dosage response, and improved solubility when compared to traditional medications are all potentially advantageous characteristics of nano-therapeutics. [9]

History of Nanomedicine

Nanomedicine is a relatively new field of study. The use of nanotechnology in pharmacology and medical technology has only been studied since the 1990s. The field of nanotechnology has only been around for a few decades. Over the course of the 20th century, high resolution microscopy developed concurrently in the fields of biology, physics, and chemistry, giving rise to new fields like microelectronics and biology. molecular biology and biochemistry The expertise of nanomedicine and nanobiotechnology, which studies cell structure and function as well as intracellular and intercellular processes [19].

This research study was only made possible at the start of the 20th century, when the development of cutting-edge microscopes—which were required in every field—opened the door to the nanocosmos. The monitoring, repair, creation, and control of human biological systems at the molecular level through the use of manmade nanodevices and nanostructures is known as nanomedicine. Understanding the concerns with nanomedicine's toxicity and environmental history are among its current challenges. Nanomedicine is a relatively new field of study. When it comes to the effects of nanoscale materials—materials whose structure is on the scale of nanometers, or billionths of a meter—nanotechnology can be applied in the medical field [20].

By interacting with biological molecules or structures, nanomaterials can acquire additional functions. Nanomaterials can be helpful for both in vitro and in vivo biomedical research and



applications since their size is comparable to that of the majority of biological molecules and structures. Contrast agents, analytical instruments, physical therapy applications, and drug delivery vehicles or channels are all made possible by nanomaterials. In the near future, nanomedicine aims to provide both clinically relevant devices and a beneficial collection of research tools.

The Nanotechnology Initiative's potential uses in pharmaceuticals could include the use of novel treatments, sophisticated drug delivery systems, and in vivo imaging procedures. Using nanoparticles, nanotechnology has made it possible to deliver medications to particular body cells [21]. Because smaller devices are less invasive and may even be implanted inside the body, adopting nanoscale materials for medical technologies has the advantage of substantially faster biochemical reaction times. Compared to standard medication delivery systems, these devices are quicker and more sensitive.

The efficiency of drug delivery through nanomedicine is a largely based upon the followings as

- The Efficient encapsulation of the drugs
- The Successful delivery of the drugs to the targeted region of the body, and
- The Successful release of the drugs in to the body.

Principles

The special qualities that materials display at the nanoscale are the basis of nanomedicine. Materials exhibit unique physical, chemical, and biological characteristics at sizes between 1 and 100 nanometers that are very different from those of their bulk counterparts [22]. These characteristics,

which can be used therapeutically, include improved surface area-to-volume ratios, quantum effects, and modified electronic configurations [23]. This scale's quantum confinement effects result in special optical, electrical, and magnetic characteristics that open up new therapeutic and diagnostic possibilities.

Transport Mechanisms

1. Passive Transport

A key mechanism in the delivery of nanomedicines is the increased permeability and retention (EPR) effect. Large endothelial cell fenestrations and poor lymphatic drainage are two architectural anomalies in tumor vasculature that cause this condition. These characteristics enable the preferential accumulation of nanoparticles in malignant tissues [24]. However, the efficiency of passive targeting can be greatly impacted by the variability of interstitial pressure and tumor vasculature.

2. Active Targeting

Precise identification of cellular receptors or disease-specific indicators is made possible by surface modification of nanoparticles with particular targeting moieties. This method entails attaching ligands to the surface of the nanoparticle, such as peptides, antibodies, or small molecules. These interactions' selectivity minimizes off-target effects while greatly increasing treatment efficacy [25].

Targeting mechanism	Cellular Uptake	Components
Passive Targeting	Accumulation in leaky vasculature; Retention due to poor lymphatic drainage	Enhanced Permeability and Retention (EPR) effect
Active Targeting	Specific cellular recognition;	Antibodies; Peptides;



(Ligand mediated)	Enhanced cellular uptake; Receptor-mediated endocytosis	Aptamers; Small molecules
Stimuli Responsive	Triggered release in specific conditions; Response to tumor microenvironment	pH-sensitive; Redox responsive; Enzyme responsive; Temperature-sensitive
Cell-Mediated	Natural targeting abilities; Dynamic response; Biological barrier crossing	Immune cells; Stem cells; Engineered cells

The Advantages of Nano Medicine

- The Drug delivery to the exact location.
- To reduce lesser side effects.
- The Molecular targeting by nano engineered devices.
- The disease Detection is relatively easy.
- No surgery required.
- The Diseases can be easily cured.
- Identify optimal drug agents, to treat the existing condition, or targeted pathogens.
- Diagnose conditions and disclose pathogens.
- Fuel high-yield production of matched pharmaceuticals.
- Locate, embed, or attach integrated or enter target tissue; configurations or pathogens.
- Dispense the ideal mass dosage of matched biological compound to the specific target locations.

The Uses of Nanomedicine

The possible uses of nanotechnology in medicine are based on three basics as:

1. The Nanomaterials and nanoinstruments which can be used as biosensors, as aids in treatment and as transporters of active substances.
2. The knowledge of molecular medicine in the fields of genetics, proteomics and synthetically produced or modified microorganisms.
3. The nanotechnologies which can be used for the rapid diagnosis and for therapy, for repair of genetic materials and for the cell surgery, as well as for the improving of natural physiological functions.

Limitations of nanomedicine

1. Production and Expansion Maintaining constant quality and reproducibility is a major difficulty in the industrial-scale manufacture of nanomedicines. To guarantee batch-to-batch homogeneity, the intricate manufacturing procedures necessitate exact control over a multitude of parameters. Therapeutic efficacy can be greatly impacted by changes in drug loading efficiency, surface characteristics, and particle size distribution. Technical challenges in preserving product requirements while attaining cost-effectiveness frequently arise during the shift from laboratory-scale production to commercial manufacture [26].
2. Uniformity Because of their distinct characteristics and behavior, the regulatory environment for nanomedicine approval is still complicated. The unique features of nanotherapeutics are difficult for current regulatory frameworks to sufficiently handle, which results in drawn-out approval procedures. The establishment of regulatory guidelines is

complicated by the absence of established techniques for characterization and quality control. The commercialization process is further complicated by the international harmonization of regulatory requirements [27].

3. Safety

3.1. Long-term Effects

It is still unclear how nanoparticles may affect biological systems in the long run. Potential buildup in organs and tissues is a concern, especially for non-biodegradable compounds. Unexpected immunological reactions or persistent inflammation may result from the interaction of nanoparticles with the immune system. Unintentional neurological consequences are a worry due to the ability for nanoparticles to overcome biological barriers, such as the blood-brain barrier [28].

3.2. Environmental Impact

The health of ecosystems is seriously threatened by the environmental fate of nanomaterials. Careful thought must be given to the possible buildup of nanoparticles in environmental matrices and their effects on different organisms. Risk assessment efforts are complicated by the difficulties in identifying and measuring nanoparticles in environmental samples [29].

4. Stability

It is very difficult to keep nanomedicine formulations stable while they are being stored and administered. Therapeutic efficacy may be impacted by physical instability, which might cause particle aggregation or alter surface characteristics. Drug leakage and surface

modification degradation are examples of chemical stability issues [30].

5. Biological Barrier

Overcoming some biological obstacles is still difficult, despite improvements in design techniques. The efficacy of passive targeting is limited by the variation in the increased permeability and retention (EPR) effect among various tumor types. Effective medication distribution may be hampered by biological barriers including cellular membranes and mucus layers [31].

6. Economic Constraints

6.1. Expenses of Development

Commercialization is severely hampered by the exorbitant expenses of developing and characterizing nanomedicines. High development costs are a result of complicated manufacturing procedures and extensive preclinical testing needs. The whole expense burden is increased by the requirement for specialized tools and knowledge [32].

6.2. Market Access

High production costs frequently result in pricey finished goods, which restrict patient affordability and market access. Different healthcare systems continue to have varied insurance coverage and payment procedures for treatments based on nanomedicine [33].

7. Clinical Challenges

7.1. Effectiveness There are particular difficulties in proving consistent treatment efficacy in clinical settings. Treatment results may be impacted by the intricacy of biological systems and individual



patient differences. Market introduction is delayed because long-term clinical trials are required to determine safety and efficacy characteristics [34]

7.2. Factors Particular to Patients Treatment efficacy may be impacted by individual differences in patient features and illness progression. Genetic and environmental factors must be taken into account while developing individualized nanomedicine techniques. Clinical implementation is complicated by patient-specific optimization [35].

Emerging trends in nanomedicine

1. Cutting-Edge Materials and Designs

Advances in materials science and engineering are driving the development of nanomedicine. DNA-based nanostructures, which provide previously unheard-of control over molecular interactions, are becoming programmable platforms for drug delivery and biosensing. Dynamic adaptability to biological conditions is made possible by smart materials that incorporate stimuli-responsive components. Improved biocompatibility and therapeutic efficacy are promised by the creation of bio-inspired materials that imitate natural biological functions [36].

2. Artificial Intelligence

2.1. Predictive Modeling:

The design and optimization of nanoparticles are being revolutionized by machine learning methods. Predicting cellular uptake patterns and nanoparticle-protein interactions is made possible by sophisticated computational models. AI-driven methods enable quick screening of treatment combinations and formulation factors [37].

2.2. Clinical Decision Support: Real-time treatment monitoring and modification are made

possible by the integration of AI with nanomedicine platforms. Based on each patient's unique reaction, predictive analytics aids in the optimization of treatment plans. The patient populations most likely to benefit from particular nanotherapeutics are identified with the help of machine learning algorithms [38].

3. Precision Medicine

3.1. Integration of Molecular Profiling Hardware specifications, validation procedures, and training requirements Highly customized therapeutic techniques are made possible by the intersection of proteomics, genomes, and nanomedicine. Patient-specific therapies are made possible by nanoplateforms that react to certain molecular signatures. Real-time monitoring of the course of the disease and the effectiveness of treatment is made possible by advanced diagnostic capabilities [39].

3.2. Platforms for Multimodal Therapy creation of integrated platforms that incorporate several therapeutic approaches into a single nanocarrier. synergistic strategies that combine new treatment methods with traditional therapies. application of treatment systems that are adaptive to the progression of disease [40].

4. Emerging Applications

4.1. Regenerative Medicine:

Tissue engineering and regenerative medicine applications are using nanomaterials more and more. Bioactive nanoparticles incorporated into advanced scaffolds facilitate wound healing and tissue regeneration. Precise control over tissue development is made possible by the controlled release of growth factors and cellular signals [41].

4.2. Applications in Neurology Treatment options for neurological illnesses are



growing thanks to innovative methods of bridging the blood-brain barrier. creation of tailored nanocarriers for the treatment of neurodegenerative diseases. combining nanomaterials with neural interfaces to enhance brain-computer interaction [42].

5. Manufacturing trends

5.1. Continuous Flow Production

using continuous production techniques to increase consistency and scalability. Real-time production parameter monitoring is made possible by sophisticated quality control systems. Automated system integration to improve production efficiency [43].

5.2. Green Manufacturing: Creating production techniques that are sustainable for the environment. application of eco-friendly products and waste reduction techniques. energy-efficient manufacturing process optimization [44].

Challenges for Nanomedicine

Despite the advantages of nanomedicine, a great deal of research is still needed to assess the toxicity and safety of numerous NPs. [10] Relatively few studies have focused on the pharmacokinetics or toxicity of NPs, while the majority of nanomedical research has focused on drug delivery. [14] Monitoring the impact of NPs on patient populations requires examining NP pharmacokinetics, pharmacodynamics, and possible long-term toxicity in vivo. [12] For researchers and the FDA, which is currently having difficulty developing testing criteria and gathering safety data, validating every nanotherapeutic agent for safety and efficacy—drug, device, biologic, or combination product—presents a huge challenge. [9, 10] Research is also required to evaluate NPs' immunogenicity. [45]

Because nanotherapeutics and diagnostics are more reactive than with their bulk counterparts.[9]

A hypersensitive reaction, which may be brought on by activation of the immunological complement system, appears to be the most commonly reported adverse event following injection of a nanotherapeutic drug. [13] It is believed that the primary molecular mechanism of in vivo NP toxicity is the production of free radicals, which induce oxidative stress. 3 When free radicals are present in excess, they can oxidize lipids, proteins, DNA, and other biological components. Aspect ratio and surface area are two fundamental properties of NPs that have been shown by several authors to exhibit pro-inflammatory and pro-oxidant properties. [14]

However, phagocytic cells' reactivity to foreign material, a lack of antioxidants, the presence of transition metals, environmental conditions, and other inherent chemical or physical characteristics can all contribute to the production of free radicals in response to an NP. [10] It may be possible to determine the key dimensions at which NPs likely to considerably concentrate in the body by conducting research to assess their size and surface characteristics. [45] Because of their small size, NPs have a greater capacity to pass through biological barriers, which may lead to their accumulation in tissues and cells. [9]

Organs like the liver and spleen may be the primary targets of oxidative stress due to the potential tissue accumulation, storage, and sluggish clearance of these potentially free radical-producing particles as well as the abundance of phagocytes in the RES. [10–13] Nano medical research is forced to concentrate mostly on polymer NPs, for which safety and efficacy data are already available, because to the absence of information regarding possible toxicity concerns. [10] Actually, the FDA has already approved a



number of nanomedicines that incorporate polymer NPs. 3 Lipid NPs are also thought to be biocompatible and acceptable, in contrast to other compounds that could become hazardous in NP form. [10] Therefore, it is far more advantageous to use biodegradable, soluble, nontoxic NPs in nanomedicines than biopersistent components, such as polymers, liposomes, and IO particles. [12]

It may be more difficult to use NPs that are not biodegradable, such as carbon nanotubes, QDs, and some metallic nanocarriers. [8–14] This feature should support attempts to find more biodegradable forms, materials, and surface treatments rather than deter nanomedical research using these NPs.

Clinical Cancer Treatment Using Nanomedicine

Among the several types of nanomedicine materials used in therapeutic cancer therapy are drug conjugates, viral vectors, polymer-based nanocarriers, lipid-based nanocarriers, and inorganic nanoparticles. An A. Viral nanoparticle therapy for cancer A sophisticated technique for producing nanoparticles for cancer treatment combines the production of therapeutic proteins with a tumor-homing virus. The pox virus's myxoma and vaccinia strains often multiply in tumor cells.

Certain characteristics of malignant cells, such as immune evasion, dysregulation of cell reproduction, and inhibition of apoptotic pathways, also aid in effective pox virus proliferation. B. Using organic nanocarriers to treat cancer Organic nanocarriers are compensated for by a number of artificial or natural materials designed for targeted or non-targeted drug delivery. They can be divided into the following major categories: pharmaceutical conjugates, lipid transporters, protein carriers, glycan carriers, and

synthetic polymer carriers. While drug conjugates have been successfully introduced into clinical settings, attempts to accomplish the same with nanocarriers made of polymers, proteins, or lipids have only been tentative.

Future prospects of nanomedicine in targeted drug delivery

Nanomedicine has enormous potential to transform personalized medicine, enhance disease detection and therapy, and promote tissue regeneration and repair. The creation of nanorobots and nanosensors capable of carrying out intricate bodily functions like drug delivery, illness detection, and tissue repair is a significant area of nanomedicine. Additionally, nanoparticles can be employed to administer several medications or therapies at once, improving the efficacy of treatments for complicated illnesses. Nanoparticles can also be employed as non-invasive diagnostic instruments to find illnesses early on.

Additionally, more accurate illness detection and diagnosis as well as more precise and effective drug administration may result from the combination of artificial intelligence with nanomedicine. But there are still obstacles to deal with, like cost-effectiveness, safety and toxicity concerns, and regulatory issues. To overcome these obstacles and realize the full promise of nanomedicine, academics, healthcare providers, and business partners must continue to invest and work together [46–48].

Applications:

1. Contrast compounds for visualizing cancer cells When exposed to UV light, cadmium selenide nanoparticles, often known as quantum dots, illuminate. These seep into cancerous tumors when injected. The glowing tumor is visible to the



surgeon, who might utilize it as a guide for more precise tumor removal techniques [49].

2. Treatments for disorders related to cancer It is possible to direct the gold nanoshells to attach to the malignant cells. By using infrared lasers to irradiate the tumor's surrounding area, the gold is heated enough to kill the cancer cells while the lasers pass through the body without heating it.

3. The uses of medical nanomaterials This could address the challenges and blood leaks that arise when a surgeon attempts to re-stitch the arteries that were cut during a heart or kidney transplant [50].

4. The diagnostic tools for nanoelectronic biosensors The usage of arthroscopes with lights and cameras during surgeries has advanced thanks to nanotechnology, allowing surgeons to do procedures with smaller incisions.

5. The applications of physical therapy In photodynamic therapy, a tiny particle is inserted into the body and recognized by external light. The particle absorbs the light, and if it is made of metal, the light's energy will heat the particle and the tissues around it [51].

6. Using neuro-electronic interfaces The development of nanodevices that will enable computers to be connected to the nervous system is the ambitious objective of the application of neuro-electronic interfaces.

7. The use of tissue repair Nanotechnology might be able to aid in tissue repair or replication. "Tissue engineering" uses appropriate nanomaterials based on scaffolds and growth hormones to artificially increase cell proliferation. For instance, scaffolds made of carbon nanotubes could be used to regrow bones. Today's traditional treatments, such as

organ transplants or artificial implants, may be replaced by tissue engineering [52].

8. The technique of molecular nanotechnology Nanorobots would be inserted into the body and used in nanomedicine to detect or heal damage and infections. Because of the inherent strength and other qualities of some kinds of carbon (diamond/fullerene composites), carbon may be the main component utilized to construct these nano robots. These robots would be made in desktop nano factories specifically designed for this purpose. Applications of nanomedicine include activity monitors, Chemotherapy, pacemakers, biochips, over-the-counter tests, insulin pumps, nebulizers, needleless injectors, medical flow sensors, blood pressure, glucose monitoring, and drug delivery systems. Nanorobots are used as miniature surgeons in nanomedicine. These devices could fix injured cells or enter cells to help or replace the damaged intracellular components. By changing or substituting DNA (deoxyribonucleic acid) molecules, the nanomachines may be able to replicate themselves or fix genetic flaws [53].

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