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Nanotechnology in drug delivery: A comprehensive review

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Abstract

Nanotechnology is reshaping pharmaceutical research by providing innovative strategies to overcome the limitations of conventional drug delivery systems. Through the design of Nano scale carriers, researchers have improved drug solubility, targeted delivery, and controlled release kinetics, thereby enhanced therapeutic efficacy and minimized side effects [1]. This review examines the evolution of Nano carriers, their mechanisms of action, clinical applications, challenges, and emerging future trends in the pharmacy field.

Keywords: Nanotechnology; Nanoparticle; Polymeric nanoparticles; Targeted drug delivery

1. Introduction

1.1. Background and Rationale

Traditional drug delivery methods often struggle with issues such as low bioavailability, rapid clearance, and non-specific distribution of active pharmaceutical ingredients (APIs) [2]. Nanotechnology offers solutions by allowing the design of carriers at the molecular scale that can encapsulate drugs, protect them from degradation, and improve their absorption in targeted tissues [3]. These innovations have broad implications for the treatment of complex diseases including cancer, neurodegenerative disorders, and genetic diseases.

Objectives

This review aims to

- Outline the historical evolution and underlying concepts of nanotechnology-based drug delivery.
- Categorize and describe various Nano carrier systems.
- Analyze mechanisms that enable targeted and controlled drug release.
- Evaluate clinical applications and present case studies.
- Discuss current challenges and potential future directions.

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2. Historical Perspective and Evolution of Nano medicine

2.1. Early Developments in Drug Delivery

Historically, pharmaceutical formulations were limited by the intrinsic properties of the drugs themselves. Many APIs exhibited low solubility or were rapidly metabolized, leading to suboptimal therapeutic outcomes [4]. Early efforts focused on chemical modifications and basic carrier systems that often-lacked specificity and control.

2.2. Emergence of Nano scale Approaches

Advancements in material science during the late 20th century paved the way for nanotechnology in drug delivery [5]. Early successes with liposomes and polymeric nanoparticles demonstrated that Nano scale formulations could significantly improve drug stability, bio distribution, and targeted delivery [6]. These developments have set the stage for the current era of personalized Nano medicine.

3. Classification of Nano carriers

Nano carriers are diverse and can be grouped based on their composition, structure, and method of drug encapsulation. Each category offers unique advantages for specific clinical applications.

3.1. Liposomal Systems

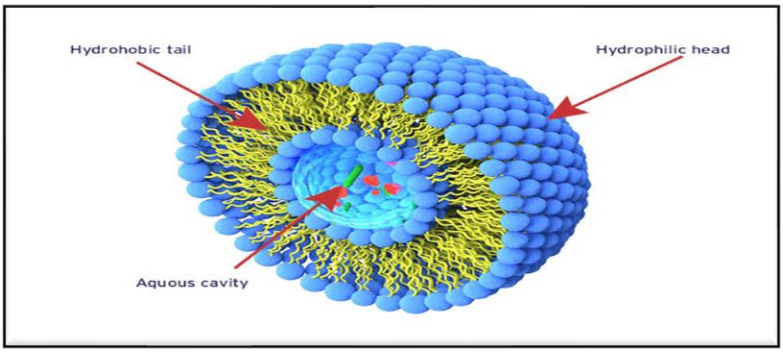

Figure 1 Non-nonic Surfactant vesicle (NSV)

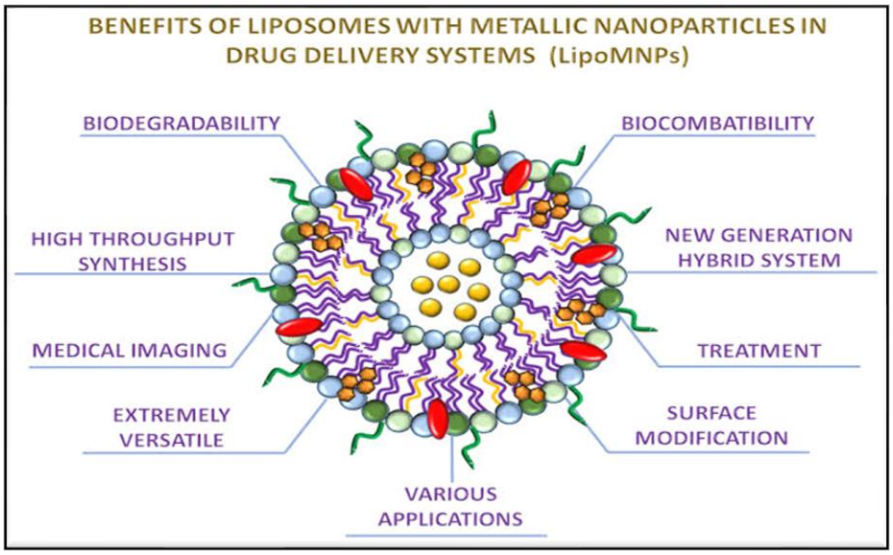

Figure 2 Benefits of Liposomes With Metalic Nanoparticles In Drug Delivery System (LipoMNPs)

3.2. Structure and Composition

Liposomes are spherical vesicles comprised of one or more phospholipid bilayers, allowing them to encapsulate both hydrophilic drugs (within their aqueous core) and hydrophobic drugs (within the lipid bilayer) [7].

3.3. Advantages and Applications

Due to their biocompatibility and biodegradability, liposomes are widely used in the delivery of anticancer agents, vaccines, and antimicrobial therapies [7]. Their ability to fuse with cell membranes enhances intracellular drug delivery.

3.4. Polymeric Nanoparticles

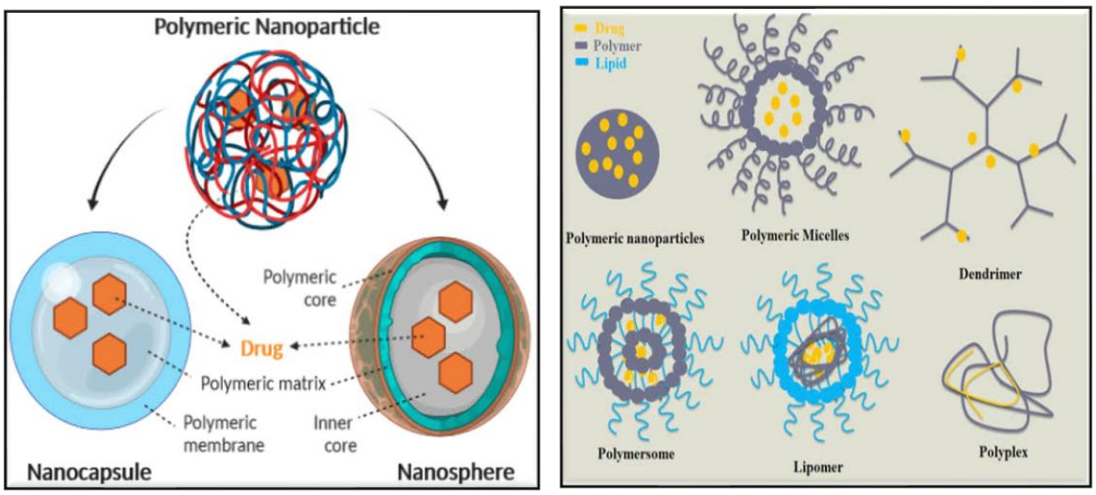

Figure 3 Illustrate various type of polymeric nanoparticles used in drug delivery system

3.5. Materials

Typically fabricated from biodegradable polymers such as poly (lactic-co-glycolic acid) (PLGA), these nanoparticles are designed for controlled and sustained drug release [8].

3.6. Mechanisms And Impact

Their tunable degradation rates and surface modifications allow for precise control over drug release kinetics and active targeting, making them invaluable in cancer therapy, gene delivery, and chronic disease management [8].

3.7. Dendrimers

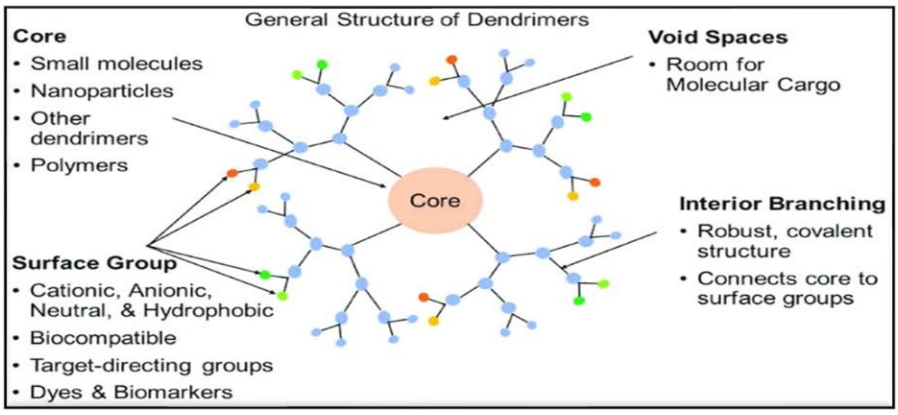

Figure 4 General structure of Dendrimers

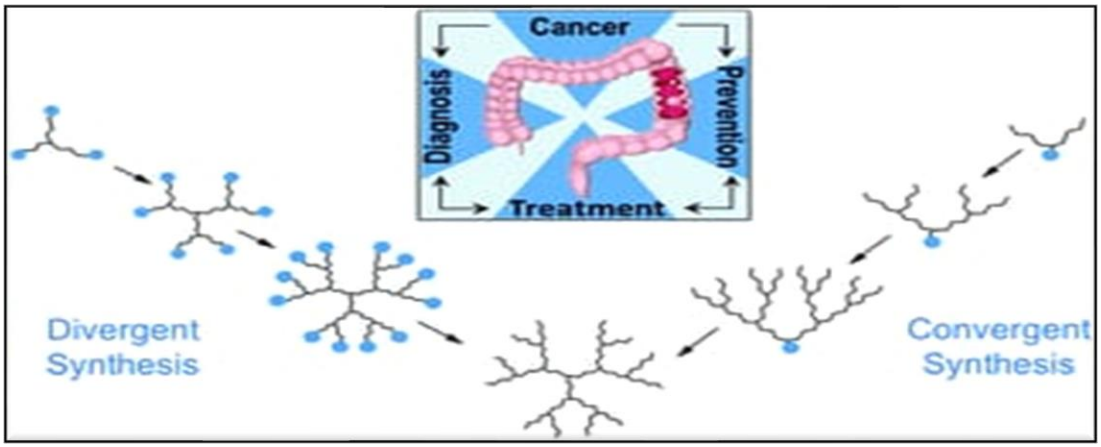

Figure 5 Dendrimers nanoparticle for colorectal cancer

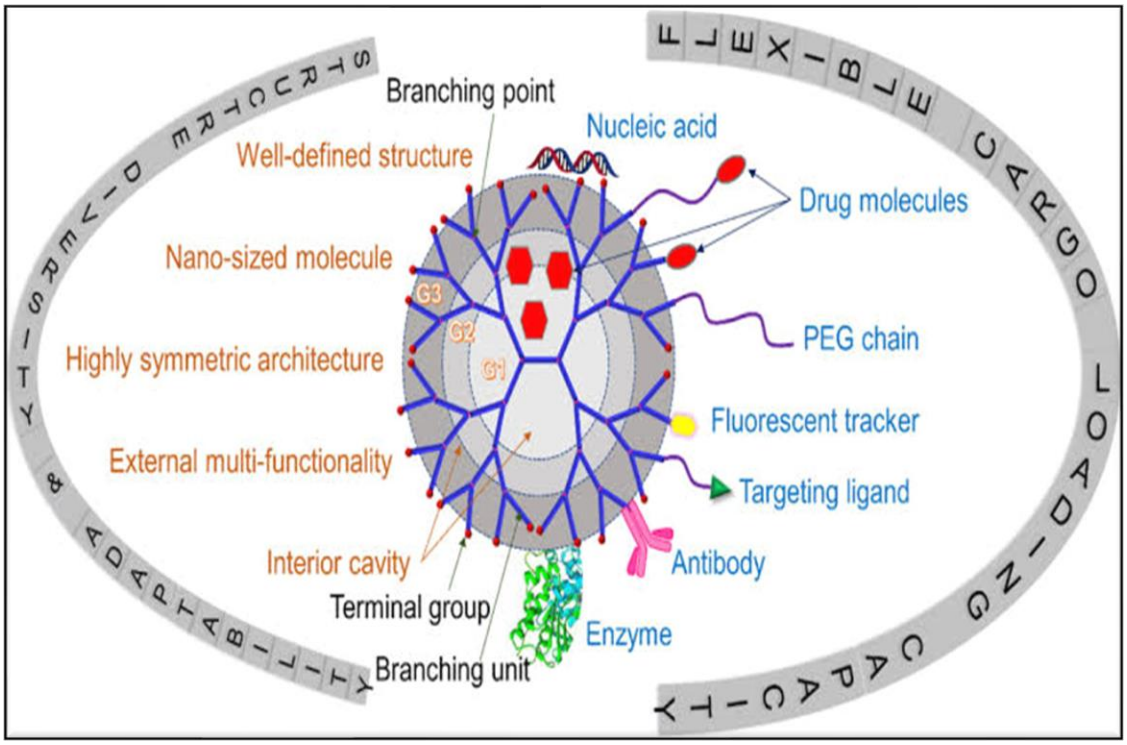

Figure 6 Structure diversity, adaptaility and flexible cargo loading capacity of dendrimers

3.8. Architecture

Dendrimers are highly branched, tree-like macromolecules with a defined, monodisperse structure. Their numerous terminal functional groups can be tailored to attach drugs, targeting ligands, or imaging agents [9].

3.9. Therapeutic Potential

Their uniform structure and customizable surface chemistry enable simultaneous delivery of multiple therapeutic agents, which is particularly useful in combination therapies applications [9].

3.10. MI cellar Nano carriers

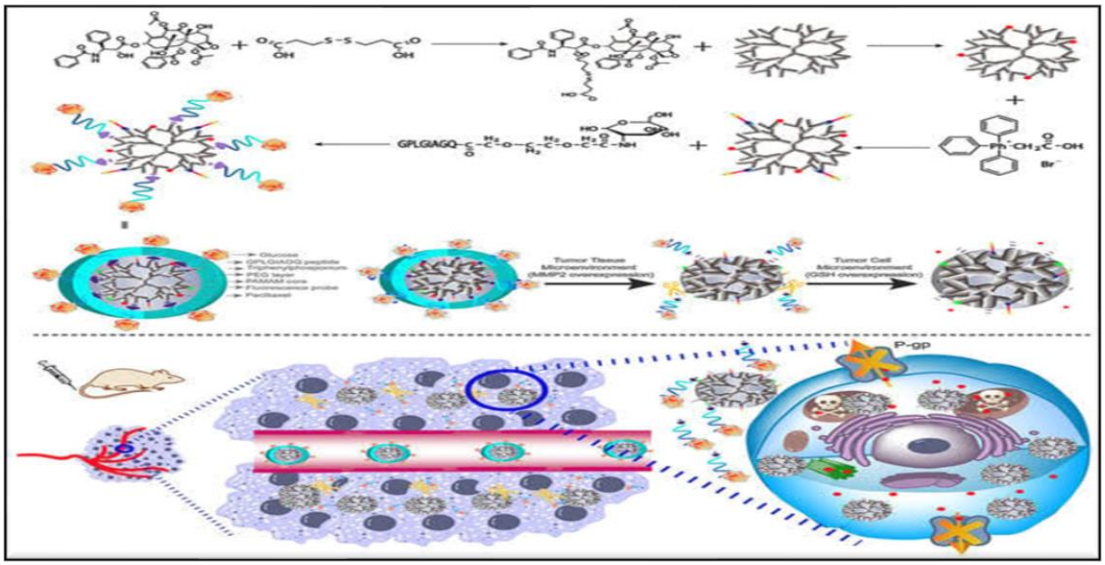

Figure 7 Schematic illustration of the glucose-PEG_peptide-triphenylphosphonium-PAMAM-PTX conjugate

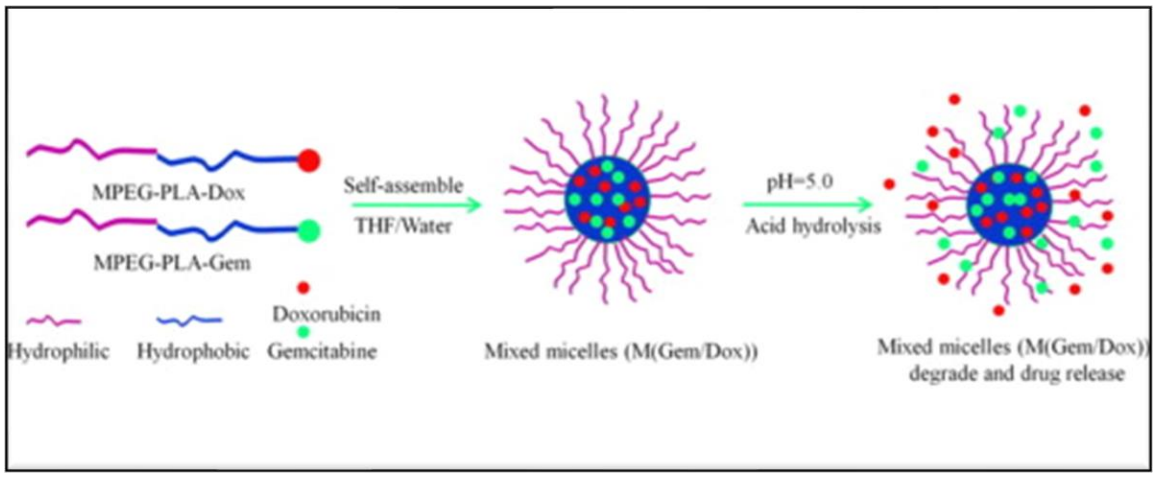

Figure 8 Micellar nanoparticles loaded with gemcitabine and doxorubicin showed synergistic effect

3.11. Self-Assembly

Micelles form through the self-assembly of amphiphilic molecules in an aqueous medium, resulting in a core–shell structure. The hydrophobic core facilitates the solubilization of water-insoluble drugs, while the hydrophilic shell stabilizes the system [10].

3.12. Clinical Relevance

Micellar systems have shown promise in enhancing the bioavailability of hydrophobic drugs and are being explored for systemic delivery with reduced toxicity [10].

3.13. Emerging Nanomaterial's

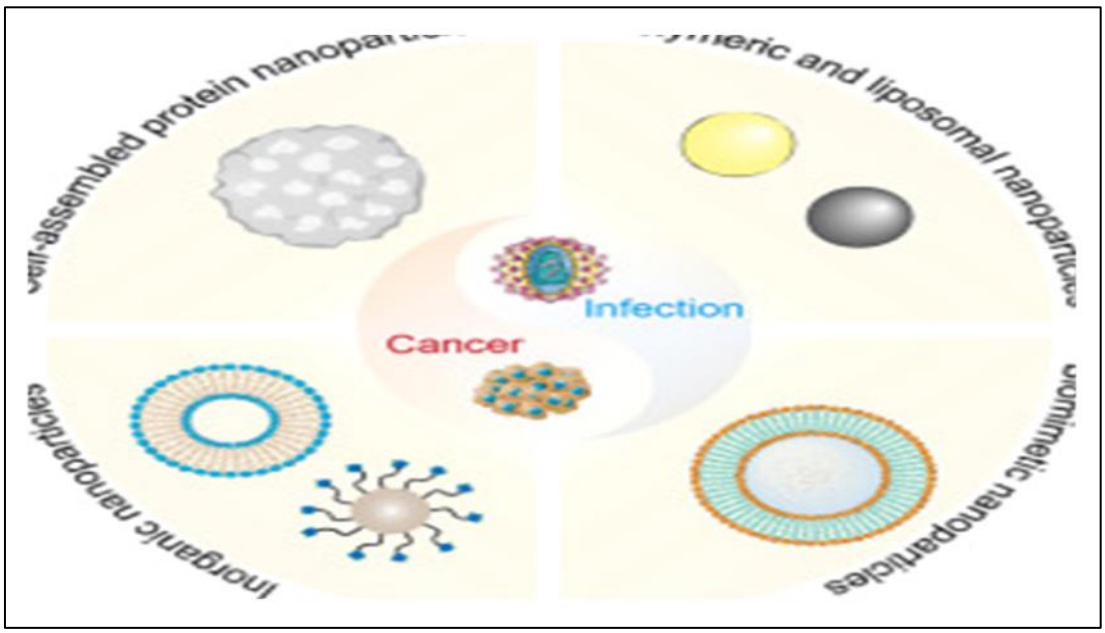

Figure 9 Emerging vaccine nanotechnology: From defense against infection to sniping cancer

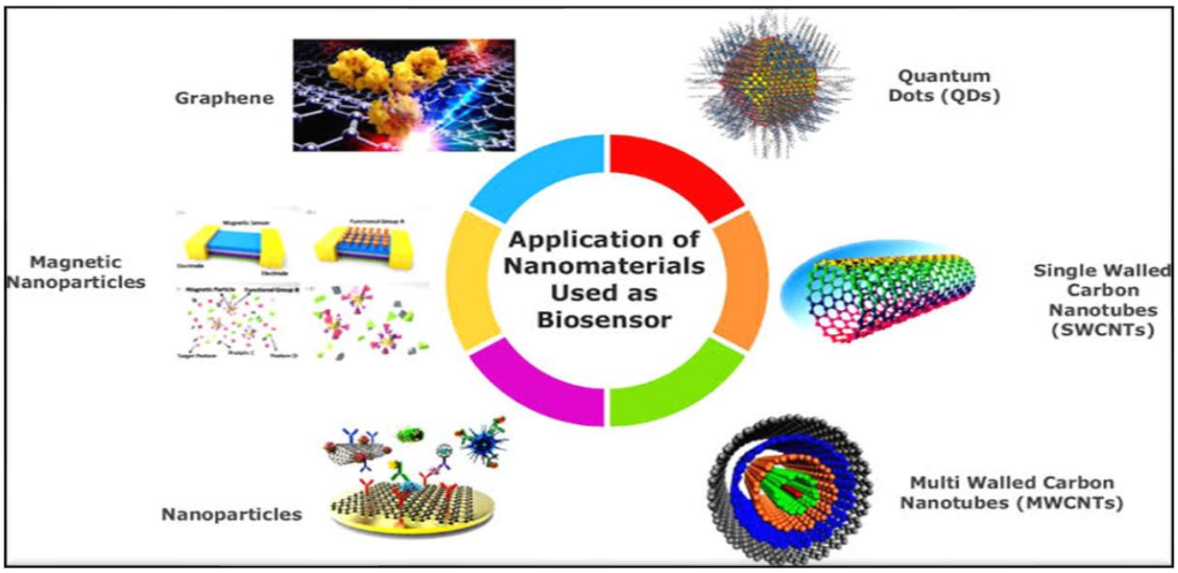

Figure 10 Application of nanomaterials used as biosensor

3.14. Metallic Nanoparticles and Quantum Dots

Nanoparticles composed of metals such as gold or silver, along with semiconductor quantum dots, possess unique optical and electronic properties that support both drug delivery and diagnostic imaging [11].

3.15. Carbon-Based Nanomaterial's

Materials like carbon nanotubes and grapheme oxide offer high surface areas and the potential for functionalization. Despite their promise, concerns regarding long-term biocompatibility and toxicity are being actively researched [11].

4. Mechanisms of Nanoparticle-Mediated Drug Delivery

Nano carriers enhance drug delivery by exploiting several mechanisms that ensure improved precision and efficacy.

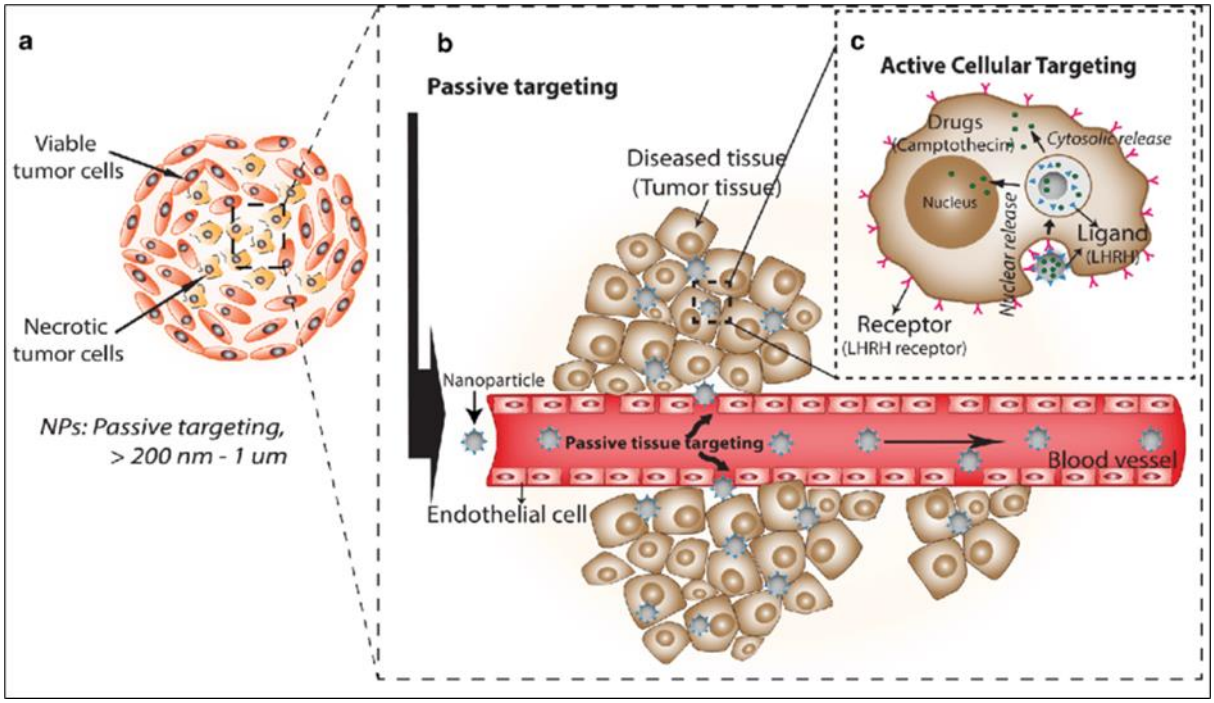

Figure 11 Nanoparticle-Mediated drug delivery

4.1. Targeted Delivery

4.1.1. Passive Targeting

Exploiting the Enhanced Permeability and Retention (EPR) effect, nanoparticles tend to accumulate in tissues with leaky vasculature, such as tumors or sites of inflammation [12]. This natural accumulation bypasses the need for active targeting strategies.

4.1.2. Active Targeting

By conjugating nanoparticles with specific ligands (e.g., antibodies, peptides), receptor-mediated uptake is enhanced, ensuring that the drug is delivered directly to the affected cells [12]. This minimizes off-target effects and improves therapeutic outcomes.

4.2. Controlled and Stimuli-Responsive Release

4.2.1. Kinetic Control

Nano carriers can be engineered to release drugs in a controlled manner through mechanisms such as diffusion, carrier degradation, or swelling-induced release [13]. This sustained release maintains therapeutic drug levels over extended periods.

4.2.2. Stimuli-Responsive Systems

Advanced Nano carriers are designed to respond to specific physiological triggers such as pH, temperature, or enzymatic activity. For instance, a nanoparticle may release its payload in the acidic microenvironment of a tumor, thus optimizing drug efficacy and reducing systemic side effects [13].

4.3. Enhanced Cellular Uptake

The small size of nanoparticles facilitates their passage through biological barriers, such as the blood–brain barrier, and promotes endocytic uptake by target cells [14]. Surface modifications further enhance cellular internalization, ensuring that therapeutic agents reach their intracellular targets effectively.

5. Clinical Applications and Case Studies

Nanotechnology-based drug delivery systems have already begun to influence clinical practice in various therapeutic areas.

5.1. Oncology

Nano carriers are at the forefront of cancer therapy. Liposomal formulations encapsulating chemotherapeutic agents like doxorubicin have improved tumor targeting while minimizing cardio toxicity [15]. Additionally, polymeric nanoparticles have been employed to overcome multidrug resistance by facilitating higher intracellular drug concentrations [15].

5.2. Gene and RNA Therapies

Nanoparticles are instrumental in the delivery of nucleic acids, including DNA, siRNA, and mRNA, which are essential for gene therapy and the treatment of genetic disorders [16]. Recent advancements in mRNA vaccine delivery have underscored the potential of nanotechnology to rapidly respond to emerging infectious diseases [16].

5.3. Neurological Disorders

Overcoming the blood–brain barrier remains a major challenge in treating neurological diseases. Nano carriers have been designed with surface modifications that enable them to traverse this barrier, thereby offering new treatment avenues for conditions such as Alzheimer's and Parkinson's diseases [17].

5.4. Infectious and Inflammatory Diseases

For antimicrobial therapies, Nano carriers improve the delivery of antibiotics by enhancing penetration into bacterial biofilms and sustaining drug release [18]. Similarly, controlled release formulations of anti-inflammatory agents have shown promise in treating chronic inflammatory conditions with reduced systemic side effects [18].

6. Challenges and Limitations

While nanotechnology offers considerable benefits, several challenges must be addressed to enable broader clinical application.

6.1. Safety and Toxicity

Despite the use of biocompatible materials, the long-term effects of Nano carriers remain under investigation. Issues such as immunogenicity and unintended accumulation in non-target tissues require thorough toxicological evaluation [19].

6.2. Manufacturing and Scalability

Producing nanoparticles with consistent quality on a large scale is challenging. Variability in particle size, surface chemistry, and drug loading can affect both safety and efficacy, necessitating stringent quality control measures [20].

6.3. Regulatory and Economic Barriers

The regulatory approval process for Nano medicines is complex due to their unique properties, and existing guidelines may not fully address their specific challenges [20]. Moreover, the high cost of production and quality assurance can limit accessibility, particularly in low-resource settings.

7. Future Perspectives and Emerging Trends

The future of nanotechnology in drug delivery looks promising, with ongoing research focused on addressing current limitations and enhancing clinical outcomes.

7.1. Personalized Nano medicine

Advances in genomics and biomarker discovery are paving the way for personalized drug delivery systems. Tailored nanoparticles can be engineered to match individual patient profiles, thereby optimizing therapeutic efficacy and minimizing adverse effects [21].

7.2. Multifunctional and Smart Nano carriers

Research is increasingly directed toward developing multifunctional Nano carriers that combine therapeutic and diagnostic capabilities (theranostics). Stimuli-responsive systems that release drugs in response to environmental cues are also under active investigation, promising more precise and effective treatments [21].

7.3. Integration with Emerging Technologies

The use of artificial intelligence and machine learning in nanoparticle design is a burgeoning field that could significantly accelerate the development of optimized drug delivery systems [22]. Moreover, integrating nanotechnology with microfluidics and 3D printing holds potential for creating advanced, customizable drug delivery platforms.

8. Conclusion

Nanotechnology has ushered in a new era for drug delivery by addressing many of the limitations inherent in traditional pharmaceutical formulations. Through the development of various Nano carriers—each with unique properties and mechanisms of action—researchers are enhancing drug stability, targeting, and controlled release. While challenges related to toxicity, manufacturing, regulation, and cost persist, ongoing innovations promise to overcome these hurdles. The future of Nano medicine lies in the convergence of personalized therapy, smart multifunctional systems, and cutting-edge computational design, all aimed at achieving more precise and effective healthcare solutions.

Compliance with ethical standards

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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