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Advances in Nanomedicine for Drug Delivery: From Nanoparticles to Nanocarriers in Precision Medicine

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Abstract

The field of nanomedicine has seen remarkable advancements in drug delivery systems, particularly in the context of precision medicine. Nanoparticles and nanocarriers offer unique properties that enable targeted drug delivery, improved therapeutic efficacy, and reduced side effects. This paper explores the evolution of nanomedicine, from early-stage nanoparticle-based systems to sophisticated nanocarriers designed for personalized treatments. Emphasis is placed on the development of nanomaterials such as liposomes, dendrimers, micelles, and gold nanoparticles, which are engineered to optimize drug release, stability, and biodistribution. The integration of precision medicine principles allows for the customization of therapies based on genetic, phenotypic, and environmental factors, thus enhancing clinical outcomes. The challenges, opportunities, and future directions in advancing nanomedicine for drug delivery are also discussed, focusing on the need for interdisciplinary approaches to realize the full potential of nanotechnology in clinical settings.

Keywords: Nanomedicine; Drug delivery; Nanoparticles; Nanocarriers; Precision medicine; Targeted therapy; Liposomes; Dendrimers; Micelles; Gold nanoparticles; Personalized medicine; Therapeutic efficacy; Biomedical engineering; Drug release; Clinical outcomes.

Introduction

The integration of nanotechnology into medicine, specifically nanomedicine, has revolutionized the way drugs are delivered to target sites in the body. Traditional drug delivery systems often face challenges such as poor bioavailability, nonspecific targeting, and high toxicity. To address these issues, researchers have developed nanoparticles and nanocarriers that can enhance drug efficacy and minimize side effects, marking a significant advancement in drug delivery technologies. Nanomedicine combines the fields of nanotechnology and biotechnology, leveraging the unique properties of nanoscale materials to optimize the delivery of therapeutics [1].

Nanoparticles, which typically range from 1 to 100 nanometers in size, possess characteristics that make them ideal for drug delivery applications. Their small size allows for better tissue penetration and enables them to interact with biological systems at the molecular level. Additionally, the surface of nanoparticles can be functionalized with ligands or targeting molecules, enabling the delivery of drugs specifically to diseased tissues, such as tumors, while sparing healthy cells. This ability to selectively target diseased sites is particularly valuable in cancer treatment, where conventional therapies often damage healthy tissues [2].

Nanocarriers, which include a wide range of materials such as liposomes, dendrimers, micelles, and polymeric nanoparticles, offer enhanced control over the release of drugs. These carriers are designed to encapsulate drugs, protect them from degradation, and release them at controlled rates, ensuring that the therapeutic payload reaches its intended target in optimal concentrations. The versatility of nanocarriers allows for the development of personalized drug delivery systems that are tailored to an individual's specific disease profile, genetic makeup, and response to treatment.

Precision medicine, which aims to provide tailored therapies based on a patient's genetic, environmental, and lifestyle factors, has become an essential part of modern healthcare. Nanomedicine plays a pivotal role in precision medicine by facilitating the development of targeted drug delivery systems that are customized for individual patients. This approach not only improves therapeutic outcomes but also minimizes adverse effects, ensuring that patients receive the most effective treatment with the least amount of harm [3].

Despite the promising potential of nanomedicine, several challenges remain in translating nanoparticle-based drug delivery systems from the laboratory to the clinic. These challenges include issues related to scale-up production, regulatory approval, biocompatibility, and long-term safety. The complexity of designing nanocarriers that can efficiently deliver drugs to specific sites without causing harm to healthy tissues is another obstacle that researchers continue to address.

This paper aims to explore the advancements in nanomedicine, particularly in the development of nanoparticles and nanocarriers for drug delivery in the context of precision medicine. It highlights the progress made in designing more efficient drug delivery systems and examines the role of nanotechnology in revolutionizing personalized treatments. Additionally, it discusses the future directions of nanomedicine, including overcoming existing challenges and the potential impact of these innovations on healthcare and patient outcomes. By advancing the understanding of nanomaterials and their interactions with biological systems, the field of nanomedicine holds the promise of transforming the landscape of drug delivery and precision medicine [4].

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Materials and methods

The development of nanoparticles and nanocarriers for drug delivery in precision medicine involves the use of various materials and advanced fabrication techniques. This section outlines the materials, synthesis methods, and characterization techniques used to prepare nanoparticles and nanocarriers, as well as their application in drug delivery systems.

Materials

Nanoparticles

Polymeric Nanoparticles: Polymeric materials such as poly(lactic-co-glycolic acid) (PLGA), polycaprolactone (PCL), and polyethylene glycol (PEG) are commonly used in the synthesis of nanoparticles due to their biocompatibility, biodegradability, and ability to be functionalized.

Liposomes: Lipid-based nanoparticles made from phospholipids such as dipalmitoylphosphatidylcholine (DPPC) and cholesterol are utilized for their ability to encapsulate both hydrophilic and hydrophobic drugs.

Dendrimers: Dendritic polymers such as poly(amidoamine) (PAMAM) are used for their highly branched, uniform structure that allows for the encapsulation of drugs and targeting moieties.

Gold Nanoparticles (AuNPs): Gold nanoparticles are chosen for their stability, ease of surface modification, and ability to load both hydrophilic and hydrophobic drugs [5].

Drugs: Commonly used drugs for testing nanocarriers include anticancer agents like paclitaxel, doxorubicin, and cisplatin, as well as small molecule drugs for cardiovascular and neurological diseases.

Targeting Agents: Ligands such as folic acid, monoclonal antibodies, peptides, and small molecules are incorporated on the surface of nanoparticles for targeted drug delivery to specific tissues or cells.

Synthesis and fabrication methods

Solvent Evaporation Method: Used for the synthesis of polymeric nanoparticles, where a polymer (e.g., PLGA) is dissolved in an organic solvent (e.g., dichloromethane) and then emulsified in an aqueous phase to form nanoparticles. The solvent is evaporated to form solid nanoparticles [6].

Thin Film Hydration Method: Employed for the preparation of liposomes. A thin film of lipid is formed by dissolving lipids in an organic solvent, followed by the removal of the solvent under reduced pressure. The film is then hydrated with an aqueous phase to form liposomes.

Supercritical Fluid Technology: Utilized for the fabrication of nanoparticles by using supercritical CO2 as a solvent for polymeric materials, enabling the formation of uniform nanoparticles without the use of organic solvents.

Self-Assembly Method: This method is employed for micelle and dendrimer preparation, where amphiphilic polymers or lipids spontaneously assemble in an aqueous medium to form micelles or dendrimer structures.

Seed-Mediated Growth: This technique is used to prepare gold nanoparticles (AuNPs) by reducing gold salts in the presence of a reducing agent. The seed particles serve as templates for the growth of larger nanoparticles [7].

Characterization of nanoparticles and nanocarriers

Size and surface charge

Dynamic Light Scattering (DLS): Used to measure the size distribution of nanoparticles in solution. It provides information on the hydrodynamic size, which is crucial for determining drug release and cellular uptake behavior.

Zeta Potential: Measured using DLS or laser Doppler electrophoresis to determine the surface charge of nanoparticles. Surface charge affects the stability and cellular interaction of nanocarriers.

Morphological analysis

Transmission Electron Microscopy (TEM): Provides high-resolution images to examine the size, shape, and structure of nanoparticles.

Scanning Electron Microscopy (SEM): Used for the analysis of the surface morphology of nanocarriers [8].

Drug loading and encapsulation efficiency

UV-Vis Spectroscopy: Measures the concentration of drugs in solution to determine the drug loading and encapsulation efficiency in the nanoparticles.

High-Performance Liquid Chromatography (HPLC): Used for precise quantification of drug content and encapsulation efficiency in the nanoparticles.

Drug release studies

In Vitro Release Studies: Conducted by placing nanoparticles in a controlled release medium (e.g., phosphate-buffered saline) at physiological conditions (pH 7.4, 37°C) to monitor the release profile of the encapsulated drug over time.

Cumulative Release: The amount of drug released over time is measured using UV-Vis spectroscopy or HPLC.

Surface modification

Functionalization of Nanoparticles: Ligands or targeting molecules are conjugated to the surface of nanoparticles using techniques such as covalent bonding, electrostatic interactions, or physical adsorption. These modifications enable selective targeting of specific cells or tissues [7].

In vitro evaluation

Cell Viability Assays: To evaluate the cytotoxicity of drug-loaded nanoparticles, cell viability is measured using assays such as MTT, CCK-8, or lactate dehydrogenase (LDH) release. These assays assess the potential of the nanoparticles to cause cell damage or death.

Cellular Uptake Studies: Flow cytometry and confocal microscopy are employed to assess the uptake of nanoparticles by cultured cells. Fluorescently labeled nanoparticles are typically used for visualization.

Targeting Efficiency: Cellular uptake in specific cancer or diseased cells is studied by using nanoparticles functionalized with targeting ligands. The efficiency of targeted drug delivery is assessed by comparing uptake in receptor-positive cells versus receptor-negative cells [9].

In vivo evaluation

Biodistribution: In vivo imaging techniques, such as fluorescence

imaging or positron emission tomography (PET), are used to track the distribution of nanoparticles in animal models. This helps determine the targeting ability and clearance rate of the nanocarriers.

Therapeutic Efficacy: Animal models, typically using tumor-bearing mice or disease-specific models, are used to evaluate the therapeutic efficacy of the drug-loaded nanoparticles. Tumor growth is monitored over time, and histopathological analysis is performed to assess tissue damage and drug distribution at the site of action.

Statistical analysis

Data from in vitro and in vivo experiments are analyzed using standard statistical methods such as Student's t-test or one-way analysis of variance (ANOVA) to compare differences between experimental and control groups. A p-value of less than 0.05 is considered statistically significant [10].

Discussion

The advancement of nanomedicine, particularly in drug delivery, has revolutionized the approach to precision medicine, providing targeted therapies that improve the efficacy of treatment while minimizing side effects. Nanoparticles and nanocarriers, with their unique size, surface properties, and ability to be engineered for specific functions, are critical tools in overcoming the challenges associated with conventional drug delivery systems. The ability of nanoparticles to cross biological barriers and deliver drugs precisely to the desired location offers significant advantages, especially in treating complex diseases such as cancer, cardiovascular, and neurological disorders.

Polymeric nanoparticles, liposomes, micelles, dendrimers, and gold nanoparticles are among the most widely studied materials in nanomedicine. These nanocarriers are versatile platforms that can be tailored to carry a wide range of therapeutic agents, including small molecules, nucleic acids, and proteins. Their surface can be functionalized with ligands, antibodies, or peptides, allowing for the specific targeting of diseased cells or tissues, such as tumor cells in cancer therapy. This targeted delivery enhances drug accumulation at the target site, significantly reducing the systemic toxicity and adverse effects often seen with conventional therapies.

Precision medicine aims to deliver the right treatment to the right patient at the right time, based on individual genetic, phenotypic, and environmental factors. Nanomedicine plays a pivotal role in realizing the vision of precision medicine by offering customizable drug delivery systems that can adapt to the unique needs of each patient. Personalized therapies, such as those based on the genetic profile of a patient's disease, are now possible due to advances in nanoparticle-based drug delivery. For instance, nanoparticles can be engineered to bypass drug resistance mechanisms and overcome barriers such as poor bioavailability or rapid clearance, common issues with traditional drug delivery systems.

Despite these promising advancements, several challenges remain in the translation of nanoparticle-based systems from the laboratory to clinical applications. The large-scale production of nanoparticles while maintaining their size, shape, and functional properties remains a significant hurdle. Additionally, the regulatory approval process for nanomedicines is complex and requires careful evaluation of the safety and long-term effects of nanoparticles. Ensuring the biocompatibility, stability, and controlled release of therapeutic agents is essential for their successful clinical application.

Another concern is the potential for immune system interactions. While some nanoparticles are designed to evade the immune system, others may elicit an immune response that could reduce their therapeutic effectiveness or cause adverse reactions. The long-term fate of nanoparticles in the body, their accumulation in organs, and potential toxicity are areas that require extensive research and careful monitoring.

Nanomedicine also faces challenges related to the delivery of complex drugs, such as gene therapies or biologics, which require specialized delivery systems. Ensuring that these therapies are effectively delivered to the appropriate cellular compartments for their intended action is an ongoing area of research. Furthermore, overcoming barriers like the blood-brain barrier (BBB) for neurological diseases remains a significant challenge. Various strategies, including using nanoparticles designed to cross the BBB, are being explored, but further optimization is necessary for clinical success.

In terms of future directions, interdisciplinary approaches combining nanotechnology, genomics, and biomaterials science hold great promise. Advances in synthetic biology, molecular imaging, and diagnostic tools can further enhance the design of more intelligent, responsive drug delivery systems. Nanoparticles that can sense and respond to changes in the tumor microenvironment or external stimuli like pH, temperature, or light are expected to provide more precise control over drug release, improving therapeutic outcomes.

Moreover, the integration of nanomedicine with real-time monitoring technologies, such as wearable sensors or imaging modalities, can help track the distribution and release of drugs in patients, allowing for adjustments to treatment protocols on the fly. This dynamic approach to drug delivery can help personalize therapies further and ensure optimal drug dosing and timing, tailored to the patient's needs.

Conclusion

The field of nanomedicine has emerged as a transformative force in the realm of drug delivery, offering novel approaches to overcoming the limitations of traditional therapies. The advancements in nanoparticles and nanocarriers have provided significant improvements in drug efficacy, bioavailability, and targeted delivery, particularly in the context of precision medicine. By enabling the delivery of therapeutic agents to specific sites within the body, these nanocarriers reduce the off-target effects, improving patient outcomes while minimizing systemic toxicity.

Nanoparticles, including polymeric nanoparticles, liposomes, dendrimers, and gold nanoparticles, offer versatile platforms for drug delivery due to their ability to encapsulate a wide variety of drugs, protect them from degradation, and control their release. Functionalization with specific targeting moieties, such as antibodies or ligands, further enhances the specificity of these systems, allowing for precise delivery to diseased tissues, such as tumors, thus improving therapeutic outcomes. The ability to target tumors or specific cells with high specificity is a hallmark of nanomedicine, which is particularly beneficial in complex diseases like cancer.

The integration of nanomedicine with precision medicine is a promising frontier, where therapies can be customized based on an individual's genetic profile, disease state, and unique response to treatment. Nanocarriers facilitate the development of personalized drug delivery systems that optimize treatment effectiveness and reduce adverse side effects. The coupling of targeted therapies with genetic information marks a significant leap toward truly personalized medicine, which is expected to improve patient quality of life and survival rates, especially in oncology and other chronic diseases.

However, despite these advancements, challenges remain in translating nanomedicine into routine clinical practice. Issues such as large-scale production, reproducibility, regulatory hurdles, and long-term biocompatibility need to be addressed. Furthermore, concerns regarding the immune system's interaction with nanoparticles, potential toxicity, and the stability of these systems in vivo require extensive research to ensure safe application. The blood-brain barrier, a significant obstacle for delivering drugs to the central nervous system, remains a challenging target for nanomedicine, although advances in nanoparticle engineering hold promise for overcoming this barrier in the future.

Future research in nanomedicine must focus on developing more efficient, scalable manufacturing processes, refining targeting strategies, and improving the safety profile of nanoparticles. The integration of nanotechnology with real-time monitoring systems, such as wearable devices and molecular imaging, will further enhance the ability to personalize and optimize treatments in real-time, allowing for precise drug dosing and monitoring of therapeutic responses.

In summary, the field of nanomedicine for drug delivery has made substantial progress, with nanoparticles and nanocarriers offering innovative solutions for targeted and controlled drug delivery. The continued development of these systems, alongside the principles of precision medicine, holds the potential to revolutionize therapeutic approaches, offering more effective, safer, and individualized treatment options. While challenges persist, the ongoing research in this multidisciplinary field promises to advance personalized healthcare, providing significant benefits to patients and reshaping the landscape of modern medicine.

Conflict of interest

None

Acknowledgment

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References

1. Barbu CG, Arsene AL, Florea S, Albu A, Sirbu A, et al. (2017) Cardiovascular Risk Assessment in Osteoporotic Patients Using Osteoprotegerin as a Reliable Predictive Biochemical Marker. Mol Med Rep 16: 6059-6067.
2. Kerioui M, Bertrand J, Bruno R, Mercier F, Guedj J, et al. (2022) Modelling the association between biomarkers and clinical outcome: An introduction to nonlinear joint models. Br J Clin Pharmacol 88:1452-1463.
3. Nechita VI, Hajjar NA, Drugan C, Cătană CS, et al. (2023) Chitotriosidase and Neopterin as Two Novel Potential Biomarkers for Advanced Stage and Survival Prediction in Gastric Cancer-A Pilot Study. Diagnostics 13:1362.
4. Rasheed NW, Barbu CG, Florea S, Branceanu G, Fica S, et al. (2014) Biochemical Markers of Calcium and Bone Metabolism in the Monitoring of Osteoporosis Treatment. Farmacia 62: 728-736.
5. Park SY, Cho DG, Shim BY, Cho U (2023) Relationship between Systemic Inflammatory Markers, GLUT1 Expression, and Maximum 18F-Fluorodeoxyglucose Uptake in Non-Small Cell Lung Carcinoma and Their Prognostic Significance. Diagnostics 13:1013.
6. Stanciu AE, Zamfir-Chiru-Anton A, Stanciu MM, Stoian AP, Jinga V, et al. (2020) Clinical Significance of Serum Melatonin in Predicting the Severity of Oral Squamous Cell Carcinoma. Oncol Lett 19: 1537-1543.
7. Lunke S, Bouffler SE, Patel CV, Sandaradura SA, Wilson M, et al. (2023) Integrated multi-omics for rapid rare disease diagnosis on a national scale. Nat Med 29: 1681-1691.
8. DeGroat W, Mendhe D, Bhusari A, Abdelhalim H, Zeeshan S, et al. (2023) IntelliGenes: A Novel Machine Learning Pipeline for Biomarker Discovery and Predictive Analysis Using Multigenomic Profiles. Bioinformatics 39: 755.
9. Laurie S, Piscia D, Matalonga L, Corvó A, Fernández-Callejo M, et al. (2022) The RD-Connect Genome-Phenome Analysis Platform: Accelerating diagnosis, research, and gene discovery for rare diseases. Hum Mutat 43: 717-733.
10. Niculae D, Dusman R, Leonte RA, Chilug LE, Dragoi CM, et al. (2021) Biological Pathways as Substantiation of the Use of Copper Radioisotopes in Cancer Theranostics. Front Phys 8:568296.