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REVIEW ARTICLE

Advances in Drug Delivery Systems

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Abstract: Drug delivery systems have undergone remarkable advancements in recent years, revolutionizing the way therapeutic agents are administered and enhancing their efficacy and safety profiles. This review explores the latest developments in drug delivery technologies, including biodegradable polymers, nanocarriers, and smart delivery systems responsive to specific physiological conditions. Nanotechnology-based delivery platforms, such as liposomes, dendrimers, and polymeric nanoparticles, have demonstrated impressive potential in improving drug targeting, bioavailability, reducing adverse effects, and facilitating controlled release. The increasing use of biodegradable polymers like poly(glycolic acid) (PGA) and poly(lactic acid) (PLA) enables localized and sustained drug delivery. Smart delivery systems employing stimuli-responsive materials enable drug release triggered by environmental cues like pH, temperature, and enzyme activity. Furthermore, the integration of personalized medicine and advanced drug delivery technologies is enabling more efficient and tailored therapeutic approaches. This review highlights the prevailing trends, challenges, and future prospects in drug delivery systems, emphasizing their pivotal role in advancing next-generation therapies

Keywords: Nanotechnology; Targeted delivery; Controlled-release formulations; Nanoparticles; Liposomes; Micelles; Implants.

1. Introduction

Drug delivery systems are technologies designed to transport therapeutic agents to their targeted site within the body in a controlled manner. The field of drug delivery has undergone remarkable advancements, revolutionizing the way medications are administered and controlled within the body. The primary objectives are to optimize the efficacy, safety, and patient compliance of drug treatments. These systems encompass a wide range of technologies and methodologies, including nanoparticles, liposomes, implants, and controlled-release formulations, tailored to address specific challenges such as limited bioavailability, non-specific targeting, and systemic side effects associated with traditional drug administration methods. [1-4] Historically, the treatment of diseases or chronic illnesses has primarily consisted of rapidly acting, simple compounds administered conventionally in forms such as tablets, capsules, liquids, aerosols, suppositories, injectables, or ointments. These conventional drug delivery systems represent the classical method for oral drug delivery. However, these common dosage forms are often accompanied by systemic adverse effects, primarily attributable to their unspecified biodistribution and lack of controlled drug release characteristics. Furthermore, conventional drug delivery systems have been found to have severe limitations, including uncontrolled release, higher doses, and frequent administration. Improving bioavailability is another major challenge in drug formulation. Over recent years, drug delivery systems have undergone significant advancements. Each drug delivery system has its unique characteristics that determine its release rate and mechanism, largely due to differences in physical, chemical, and morphological properties, which ultimately affect their affinities for various drug substances. Studies have identified diffusion, chemical reactions, solvent interactions, and stimuli control as major release mechanisms. One of the key objectives of drug delivery systems is to enhance the efficacy of medications by delivering them to specific target sites within the body in a controlled manner. [5-7] By overcoming physiological barriers and optimizing drug release kinetics, these systems offer a tailored approach to treatment, promoting better patient compliance and therapeutic outcomes. From conventional oral dosage forms to cutting-edge nanotechnology-based delivery systems, the evolution of drug delivery has paved the way for personalized and precision medicine interventions.

This review discusses various aspects of drug delivery systems, including targeted drug delivery strategies that exploit biological markers for site-specific action, controlled release mechanisms that sustain drug levels over extended periods, and nanotechnology applications that enable novel delivery platforms with enhanced efficacy and safety profiles. By comprehensively examining these advancements and innovations, this review aims to shed light on the current state of drug delivery research, identify challenges, and outline future directions for the development of next-generation drug delivery systems.

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2. Advanced Drug Delivery Systems

The successful development of drug delivery systems based on organic, inorganic, and hybrid nanoparticles as drug carriers for active targeting has advanced significantly in recent years. More recently, drug delivery methods have been developed with improved properties, such as reduced particle size, enhanced permeability, increased solubility, efficacy, stability, reduced toxicity, and prolonged delivery. [8,9] Compared to traditional dosage forms, they can greatly enhance the performance of the medicinal agent. Recognized as the most recent innovations, advanced drug delivery systems offer a deeper understanding of the pharmacokinetic and pharmacodynamic behavior of drugs. These drug delivery systems act as carriers, capable of transporting materials to the site of action and maintaining drug concentrations within the therapeutic range for extended periods. [10]

2.1. Targeted Drug Delivery System

Targeted drug delivery aims to increase the concentration of the drug in the targeted tissues while reducing the relative concentration in the remaining tissues. The drug is thereby localized to the intended site, minimizing its effects on surrounding tissues. Moreover, drug efficacy is maximized as drug localization prevents drug loss. Numerous carriers, including liposomes, microspheres, serum proteins, immunoglobulins, erythrocytes, and niosomes, have been employed to target drugs. A promising targeted drug delivery technique combines therapeutic molecules with nanoparticles and the construction of appropriate targeting pathways to deliver various molecules to precise locations in the body. For efficient targeting, the drug delivery system (DDS) must remain in the physiological system for the appropriate duration to target specific cells and tissues and release the delivered drug while avoiding destruction by the immune system. [11]

Nanoparticles can achieve the ability to concentrate in areas of exclusively diseased tissue through passive or active targeting methods. According to a study by Murugun, this drug delivery technique works well when utilized. Using polyacrylic acid chitosan surface-modified mesoporous silica nanoparticles (MSN), topotecan (TPT) and quercetin (QT) were delivered to target triple-negative breast cancer cells (TNBC) (MDA-MB-231) and multidrug-resistant breast cancer cells (MCF-7). Arg-Gly-Asp (RGD) peptide sequences were grafted onto the surface of the nanoparticles to efficiently target αvβ3 integrin. The RGD peptide facilitated cellular uptake and efficient release of the encapsulated drugs in both cancer cell lines. Structural, molecular, and cell death alterations were observed in the cellular nucleus, endoplasmic reticulum, and mitochondria, and a synergistic antiproliferative effect was noted. [12-14]

Another study by Wu et al. demonstrated a higher release of methotrexate (MTX) from Fe3O4MgAl-LDH (layered double hydroxide) nanoparticles with a diameter of approximately 230 nm. They recorded an 84.94% release in the tumor with a pH of 3.5 within 48 hours. Higher anticancer activity was observed in all cell lines used in their investigation. This strategy was employed by Lin et al. to target HeLa cells, where 10-hydroxycamptothecin (HCPT) and mitomycin C (MMC) were co-delivered using a folate-functionalized soybean phosphatidylcholine micellar nano-formulation to assess their therapeutic impact on HeLa cells. [15-17]

2.2. Nanotechnology

Nanoparticles are particulate dispersions or solid particles with a size range of 10–1000 nm. In a nanoparticle matrix, the drug is dissolved, entrapped, encapsulated, or bound. Depending on the preparation technique used, nanoparticles, nanospheres, or nanocapsules can be obtained. Nanospheres are matrix systems where the drug is uniformly and physically dispersed, while nanocapsules are systems where the drug is contained within a hollow core surrounded by a special polymer membrane. More than fifty years have passed since the first liposome was illustrated in 1964, and the FDA has approved more than fifty drugs containing nanoparticles. Engineered nanoparticles have great potential to increase the specificity of treatment and disease detection. [18] Through cell-specific targeting, molecular transport to organelles, and other strategies, nanotechnology could help overcome the drawbacks of conventional administration, from large-scale problems like biodistribution to smaller-scale obstacles like intracellular trafficking. Nanoparticles (NPs) can enhance the stability and solubility of encapsulated cargos, promote movement across membranes, and prolong circulation periods, thereby improving safety and effectiveness. [19]

Due to their small size and unique properties, nanoparticles (NPs) offer a wide range of applications and a greater potential to advance various scientific fields. Nanoparticles (NPs) and the nanodevices that underpin nanomedicine can be used to treat, diagnose, track, and manage a range of diseases, including cancer. By utilizing nanotechnology, a number of nanoparticulate drug delivery systems (NPDDSs) have emerged and are currently being employed as drug delivery methods. Despite the benefits, nanoparticles do have certain drawbacks. For instance, their large surface area and small size can make handling nanoparticles in liquid and dry forms challenging due to particle-particle aggregation. Furthermore, small particle size and vast surface area can easily lead to limited drug loading and burst release. Resolving these practical issues is necessary before the clinical application or commercialization of nanoparticles. The current study covers release control, surface modification concerns, drug loading techniques, nanoparticulate drug delivery systems, and potential applications of nanoparticles. Nanoparticles have shown promising results in various applications, including targeted drug delivery, gene therapy, and bioimaging. Their small size allows

them to penetrate physiological barriers, enabling site-specific delivery and minimizing off-target effects. Nanoparticles can be functionalized with targeting ligands, such as antibodies, peptides, or small molecules, to selectively bind to specific cells or tissues, enhancing the therapeutic efficacy and reducing potential side effects. [20]

In gene therapy, nanoparticles can serve as carriers for genetic material, protecting it from degradation and facilitating its delivery into target cells. This approach has shown potential in treating genetic disorders, cancer, and other diseases where gene delivery is crucial. Bioimaging is another area where nanoparticles have made significant contributions. Nanoparticles can be loaded with contrast agents or fluorescent dyes, allowing for improved imaging and diagnosis of various conditions, including cancer, cardiovascular diseases, and neurological disorders. Several types of nanoparticles have been explored for drug delivery applications, including liposomes, polymeric nanoparticles, dendrimers, and inorganic nanoparticles like gold and iron oxide nanoparticles. Liposomes are spherical vesicles composed of phospholipid bilayers, capable of encapsulating both hydrophilic and hydrophobic drugs. They have been extensively studied for targeted drug delivery, gene delivery, and imaging applications due to their biocompatibility and ability to protect encapsulated cargo from degradation. [21]

Polymeric nanoparticles, such as those made from poly(lactic-co-glycolic acid) (PLGA), are versatile carriers that can be tailored for controlled and sustained drug release. They can encapsulate a wide range of therapeutic agents, including small molecules, proteins, and nucleic acids, and can be functionalized with targeting moieties for specific delivery. Dendrimers are highly branched, monodisperse polymeric nanostructures with well-defined sizes and shapes. Their unique architecture allows for precise control over drug loading and release kinetics, making them attractive candidates for drug delivery applications. Inorganic nanoparticles, such as gold and iron oxide nanoparticles, have been investigated for their potential in drug delivery, imaging, and hyperthermia-based cancer therapy. [22] Gold nanoparticles can be functionalized with targeting ligands and therapeutic agents, while iron oxide nanoparticles have been explored for magnetic resonance imaging (MRI) and targeted drug delivery applications. Despite the promising potential of nanoparticles in drug delivery, several challenges need to be addressed, including biocompatibility, toxicity, and clearance from the body. Extensive research is ongoing to optimize nanoparticle design, surface modifications, and targeting strategies to enhance their safety and efficacy profiles.

2.3. Controlled-Release Formulations

Conventional drug formulations are frequently associated with antimicrobial resistance, immunocompromised hosts, and unwanted side effects. Drugs with a short biological half-life, such as non-steroidal anti-inflammatory drugs (NSAIDs), are often administered in bulk doses to ensure immediate effects. However, this can lead to fluctuations in drug plasma concentrations and systemic toxicity, potentially causing damage to the gastric mucosa, intestinal bleeding, and peptic ulcers. The primary goal in the design of a controlled release system is to create a device that can continuously release drugs at a zero-order rate over an extended period. In addition to the beneficial effects of reduced fluctuations in drug blood levels, patients benefit greatly from fewer dose intervals. [23] As the technologies available to fabricate such products have evolved significantly, and numerous vendors are providing excipients for controlled-release purposes, an increasing number of oral products are being formulated and marketed as controlled-release products.

Controlled-release products find another common application in drug distribution through body orifices. This is particularly relevant for ocular medications, as the delivery requirements may vary for different sections of the eye. Nonetheless, the goal is often to utilize nano-formulations to enhance absorption. Implants, nanocarrier systems, or in-situ gels may be employed to facilitate prolonged ocular retention and release. [24] The ideal formulation should have a high precorneal residence time with minimal non-specific drug tissue accumulation to deliver therapeutic drug levels to the ocular surface or into the anterior and posterior ocular tissues. Such a formulation may replace the invasive drug administration method of injections. The fundamental concept behind a controlled-release drug delivery system is to maximize a drug's utility by minimizing side effects and curing or controlling a disease condition as quickly as possible with the least amount of drug administered via the most appropriate route. This is achieved by optimizing the drug's biopharmaceutics, pharmacokinetics, and pharmacodynamics properties. Certain aspects, such as dosage management, regulated release rate, and site targeting, are absent from immediate-release drug delivery methods. Over the course of a prescribed treatment period, the drug should be delivered via an optimal drug delivery system at a rate determined by the body's needs.

2.4. Implantable Drug Delivery Systems

Significant efforts have been made to develop platforms, including implantable drug delivery systems (IDDSs), that can better adhere to treatment regimens and release drugs at specific times and locations. Notable advancements include cell-mediated neurotrophin release, the creation of a hydroxyapatite-supported system, biodegradable polymer-based implants, and multiclass and multidrug delivery systems. These developments emphasize the current advances in pharmaceutical technology and polymer chemistry that have produced complex implants, such as customized 3D-printed implants and on-demand drug release systems. [25]

Implantable drug delivery systems offer several advantages over conventional drug administration methods. They can provide localized and sustained drug release, minimizing systemic exposure and associated side effects. These systems can maintain constant drug levels within the therapeutic window, improving treatment efficacy and patient compliance. Additionally, they can overcome physiological barriers, such as the blood-brain barrier, enabling targeted delivery to specific organs or tissues. Various materials have been explored for the development of implantable drug delivery systems, including biodegradable and non-biodegradable polymers, ceramics, and hydrogels. Biodegradable polymers, such as poly(lactic-co-glycolic acid) (PLGA), polycaprolactone (PCL), and poly(glycerol sebacate) (PGS), are widely used due to their biocompatibility and tunability in terms of degradation rates and drug release kinetics.

Non-biodegradable polymers, like silicone and ethylene-vinyl acetate (EVA), have also been employed in implantable systems, offering long-term drug delivery capabilities. Ceramic materials, such as hydroxyapatite and calcium phosphates, have been explored for bone-related applications due to their biocompatibility and osteoconductive properties. Hydrogels, composed of hydrophilic polymeric networks, have gained significant attention due to their ability to mimic the extracellular matrix and provide a controlled release environment for various therapeutic agents, including proteins, peptides, and small molecules. Implantable drug delivery systems can be designed to release drugs through various mechanisms, such as diffusion, osmotic pressure, or environmental stimuli (e.g., pH, temperature, or enzymatic activity). These systems can be tailored to achieve desired release profiles, including zero-order, pulsatile, or triggered release, based on the therapeutic requirements. Moreover, the integration of advanced technologies, such as microelectromechanical systems (MEMS) and wirelessly controlled devices, has enabled the development of intelligent and responsive implantable drug delivery systems. These systems can be programmed to release drugs on demand or in response to specific physiological signals, providing personalized and precise therapeutic interventions. [26]

While implantable drug delivery systems offer numerous advantages, there are challenges that need to be addressed, such as biocompatibility, long-term stability, and the potential for adverse reactions or implant rejection. Extensive research and clinical studies are ongoing to optimize the design, materials, and fabrication processes of these systems to ensure their safety and efficacy in various therapeutic applications.

2.5. Smart Drug Delivery Systems

Smart drug delivery systems are designed to respond to specific physiological or environmental stimuli, enabling targeted and controlled release of therapeutic agents. These stimuli-responsive systems exploit changes in factors such as pH, temperature, enzyme activity, or external triggers like magnetic fields or ultrasound, to initiate drug release at the desired site. pH-responsive drug delivery systems are particularly advantageous for targeting specific regions of the body with varying pH levels, such as the gastrointestinal tract or tumor microenvironments. These systems are often based on polymers that undergo conformational changes or solubility transitions in response to pH changes, leading to drug release. Examples include polymers like poly(acrylic acid) (PAA), poly(methacrylic acid) (PMAA), and poly(L-histidine) (PHis), which exhibit pH-dependent swelling or dissolution behavior. [27]

Temperature-responsive drug delivery systems are designed to release their payload at specific temperature ranges, making them suitable for applications like hyperthermia-based cancer therapy or targeted delivery to sites with elevated temperatures due to inflammation or infection. Polymers like poly(N-isopropylacrylamide) (PNIPAAm) and poly(ethylene oxide)-poly(propylene oxide)-poly(ethylene oxide) (PEO-PPO-PEO) triblock copolymers exhibit lower critical solution temperature (LCST) behavior, undergoing phase transitions at specific temperatures, enabling controlled drug release. Enzyme-responsive drug delivery systems exploit the presence or activity of specific enzymes at target sites to trigger drug release. These systems are particularly useful for targeting diseases or conditions associated with dysregulated enzyme activity, such as cancer, inflammation, or cardiovascular disorders. Polymers containing enzyme-cleavable linkages or peptide sequences can be designed to release their cargo upon enzymatic degradation.

External stimuli-responsive drug delivery systems utilize physical triggers, such as magnetic fields, ultrasound, or light, to initiate drug release. These systems often incorporate magnetic nanoparticles, sonosensitive polymers, or photosensitive materials that respond to the applied stimulus, enabling spatial and temporal control over drug delivery. In addition to these stimuli-responsive mechanisms, smart drug delivery systems can incorporate multiple stimuli-responsive components or combine different strategies to achieve enhanced specificity and control over drug release. For instance, multifunctional nanocarriers can be designed to respond to various stimuli, such as pH and temperature changes, enabling site-specific targeting and controlled release. The development of smart drug delivery systems has the potential to improve therapeutic outcomes by enhancing drug bioavailability, reducing off-target effects, and enabling personalized treatment regimens. However, challenges remain in optimizing the design, stability, and biocompatibility of these systems, as well as ensuring their robust performance in complex biological environments. [28]

Ongoing research efforts are focused on exploring new stimuli-responsive materials, developing multi-responsive systems, and integrating advanced technologies like microfluidics and nanotechnology to create sophisticated drug delivery platforms with enhanced precision and efficacy.

2.6. Lipid-based Drug Delivery Systems

Lipid-based drug delivery systems have gained significant attention due to their ability to enhance the solubility, bioavailability, and permeability of poorly water-soluble drugs. These systems utilize various lipid components, such as oils, surfactants, and solid lipids, to solubilize or encapsulate the drug molecules, facilitating their absorption and delivery. One of the most widely explored lipid-based drug delivery systems is self-emulsifying drug delivery systems (SEDDS). These systems are isotropic mixtures of oils, surfactants, and co-solvents that can spontaneously form oil-in-water emulsions when introduced into an aqueous environment, such as the gastrointestinal tract. The resulting emulsions can improve drug solubilization and enhance absorption by increasing the surface area available for dissolution and facilitating permeation through biological membranes. [29]

Liposomes are another important class of lipid-based drug delivery systems. These are spherical vesicles composed of one or more concentric phospholipid bilayers surrounding an aqueous core. Liposomes can encapsulate both hydrophilic and hydrophobic drugs, protecting them from degradation and enabling targeted delivery. Various liposomal formulations have been developed, including conventional liposomes, PEGylated liposomes, and ligand-targeted liposomes, to improve stability, circulation time, and targeting specificity. Solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) are lipid-based nanocarriers composed of solid lipids and surfactants. These systems offer several advantages, including controlled release properties, improved stability, and the ability to incorporate both lipophilic and hydrophilic drugs. SLNs and NLCs can be designed to target specific tissues or cells by incorporating targeting ligands or modifying their surface properties. Lipid-based drug delivery systems have shown promising results in addressing the challenges associated with poorly water-soluble drugs, which account for a significant portion of the drug candidates in development. By improving solubility and bioavailability, these systems can enhance the therapeutic efficacy of drugs while minimizing potential side effects and toxicity. Additionally, lipid-based systems can be tailored to achieve desired release profiles, such as sustained or controlled release, by modifying the composition and ratios of lipid components. They can also be combined with other drug delivery strategies, such as nanoparticles or stimuli-responsive materials, to create advanced delivery platforms with enhanced functionality and performance.

However, challenges remain in optimizing the stability, reproducibility, and scale-up of lipid-based drug delivery systems, as well as addressing potential interactions with food components and physiological barriers. Ongoing research efforts focus on developing novel lipid formulations, improving manufacturing processes, and understanding the in vivo behavior and fate of these systems to ensure their safe and effective clinical translation. [30]

2.7. Personalized Drug Delivery

The integration of personalized medicine and advanced drug delivery technologies has opened up new avenues for tailored and efficient therapeutic interventions. Personalized drug delivery aims to customize the dosage, release kinetics, and targeting of drugs based on individual patient characteristics, such as genetic profiles, disease status, and physiological factors. One approach to personalized drug delivery involves the use of pharmacogenomics, which examines the influence of an individual's genetic makeup on their response to drugs. By identifying genetic variations that affect drug metabolism, transport, or target interactions, personalized drug delivery systems can be designed to optimize drug exposure and minimize adverse effects for each patient.

For instance, in cancer therapy, personalized drug delivery systems can be developed to target specific molecular markers or genetic aberrations present in a patient's tumor. This can be achieved through the use of targeted nanocarriers or stimuli-responsive systems that selectively release drugs in the tumor microenvironment, enhancing therapeutic efficacy while reducing systemic toxicity. Another aspect of personalized drug delivery involves the development of patient-specific implantable or injectable drug delivery systems. These systems can be tailored to release drugs at specific rates and durations based on individual patient needs, ensuring optimal drug exposure and minimizing fluctuations in drug levels. Advanced manufacturing techniques, such as 3D printing, have facilitated the production of personalized drug delivery devices with customized geometries, release profiles, and material compositions. These patient-specific devices can be designed based on medical imaging data and tailored to the unique anatomical features and therapeutic requirements of each individual. Furthermore, the integration of biosensors, microfluidics, and closed-loop feedback systems into drug delivery platforms enables real-time monitoring and adjustment of drug release based on physiological responses or therapeutic outcomes. This approach allows for dynamic and responsive drug delivery, ensuring optimal therapeutic efficacy while minimizing potential side effects. While personalized drug delivery holds great promise, several challenges need to be addressed, including the development of robust and scalable manufacturing processes, regulatory considerations, and the integration of personalized medicine strategies into clinical practice. Interdisciplinary collaboration among researchers, clinicians, and regulatory bodies is crucial to overcome these challenges and realize the full potential of personalized drug delivery in improving patient outcomes and healthcare. [31]

3. Challenges and Future Directions

While the field of drug delivery systems has witnessed remarkable advancements, several challenges remain that need to be addressed to fully harness the potential of these technologies. One of the primary challenges is ensuring the biocompatibility and safety of drug delivery systems, particularly those involving nanoparticles or novel materials. Extensive in vitro and in vivo studies are required to assess the potential toxicity, biodistribution, and clearance mechanisms of these systems before clinical translation. Another challenge lies in the scale-up and manufacturing of advanced drug delivery systems. Many of these systems involve complex formulations or intricate fabrication processes, which can pose difficulties in scaling up production while maintaining consistent quality and performance. Developing scalable and cost-effective manufacturing processes is crucial for the widespread adoption of these technologies in clinical practice. [1, 4, 19]

Regulatory considerations also play a significant role in the development and commercialization of drug delivery systems. As these technologies continue to evolve, regulatory agencies must establish clear guidelines and standards to ensure the safety, efficacy, and quality of these products. Harmonization of regulatory frameworks across different regions is also important to facilitate the global distribution and adoption of these innovations. Additionally, the translation of drug delivery systems from bench to bedside requires close collaboration between researchers, clinicians, and industry partners. Interdisciplinary efforts are needed to bridge the gap between fundamental research and clinical implementation, ensuring that these technologies address real-world medical needs and are effectively integrated into clinical practice. Future directions in the field of drug delivery systems are expected to focus on the development of more sophisticated and intelligent systems that can adapt to dynamic physiological conditions and provide personalized treatment. The integration of biosensors, microfluidics, and closed-loop feedback systems into drug delivery platforms will enable real-time monitoring and adjustment of drug release based on individual patient responses and therapeutic outcomes.

Moreover, the convergence of nanotechnology, biomaterials, and cellular engineering will pave the way for the development of biomimetic drug delivery systems that can interact with biological systems at the molecular level, enhancing targeting specificity and minimizing off-target effects. The use of advanced computational techniques, such as in silico modeling and simulation, will play a crucial role in optimizing the design and performance of drug delivery systems, enabling more efficient and cost-effective development processes.

4. Conclusion

The integration of drug delivery technologies with other therapeutic modalities, such as gene therapy, immunotherapy, and regenerative medicine, will open up new avenues for synergistic and multimodal treatment approaches, addressing complex medical conditions more effectively. In conclusion, the field of drug delivery systems has witnessed remarkable advancements, driven by the convergence of various scientific disciplines and technological innovations. While these advancements have addressed many challenges associated with traditional drug delivery methods, ongoing research efforts are focused on developing more sophisticated, personalized, and intelligent drug delivery systems to improve therapeutic outcomes and patient care.

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