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Nanomedicine: Targeted Drug Delivery Systems

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ABSTRACT

Nanomedicine has transformed medication delivery, especially for life-threatening disorders. Nanomedicine's targeted drug delivery systems (TDDS) and nanoparticle technologies for improved treatment are covered in this article. Nanotechnology delivers drugs precisely via passive and active targeting, minimising systemic toxicity and enhancing therapeutic results. Liposomes and polymeric nanoparticles are reviewed for cancer treatment. TDDS is promising but presents toxicity, scalability, and clinical translation issues. Future directions emphasise bioinspired nanotechnologies and personalised therapy to overcome these obstacles.

Keywords: Nanomedicine, Targeted drug delivery, Nanoparticles, Liposomes, Polymeric nanocarriers.

INTRODUCTION

The convergence of biological sciences with other fields has led to the emergence of nanobiotechnology and nanomedicine. These disciplines involve monitoring, repairing, constructing, and controlling human biological systems at the molecular level using engineered devices and nanostructures. Nanomedicine also has applications such as drug targeting, gene therapy, nanosurgery, and tissue engineering. Nanoscale materials and devices offer the advantage of designing and generating unique structures and assemblies. In medicine, nanotechnology holds promise for early diagnosis, improved treatment, reduced side effects, and the enhancement of physiological systems at the molecular level [1]. In an era of modern pharmaceutical medicine, the utilization of ultrafine drug delivery systems for the therapy of different life-threatening diseases holds further potential. Advancements in the field of nanotechnology have resulted in the development of different drug delivery systems. Some of the most important ones include liposomes, solid lipid nanoparticles, nano drugs, nano carriers, microemulsions, and nanoparticles (nanosuspensions). The nanoparticles possess a variety of features such as high dose-loading capacity, small size preventing reticuloendothelial system's (RES) clearance, and a concentration-dependent escape from the spleen and liver's entrapment, freely passing through capillaries, passive and active targeting. This article seeks to review the different aspects of drug targeting, the various carriers utilized for delivering targets, types of targeting, mechanisms of drug release, evaluation parameters, applications, the need for targeting, and a great emphasis on the application of targeting in the form of different drug delivery systems, especially polymeric nanoparticles [2].

OVERVIEW OF NANOTECHNOLOGY IN MEDICINE

Nanotechnology is one of the significant scientific pursuits in the 21st century that receives increasing attention throughout healthcare disciplines, computer science, electronics, and other related disciplines. The unique properties of matter, including size optimization and modified physical and chemical characteristics that vary from macroscopic matters, introduce new tools and techniques for medical science [3]. Nanomedicine applies nanotechnology for treating diseases, monitoring transport systems at nanoscales, and improving drug delivery. It includes vaccines, implants, imaging agents, injectable medicines, and site-specific targeting. Recent advancements in nanoparticle medications provide biocompatibility, desired physicochemical features, and biodegradability, ensuring safer human use. Targeted drug delivery aims to minimize damage to healthy tissues and organs, focusing on accurate and effective therapy [4].

PRINCIPLES OF TARGETED DRUG DELIVERY

The underlying principles of targeted drug delivery are based on the selective accumulation of biologically active compounds at their site of action, versus non-specific and undesirable distribution of these substances and/or their metabolites throughout the body, which is the goal of traditional medicine. The basis for targeted drug treatment is the use of biological systems capable of interacting with a drug carrier and transporting it to a place where it should act. The most common strategy is drug delivery that uses the natural ability of cells to take up and process proteins, lipids, and carbohydrates along with associated small and macromolecular transmembrane components. The transported complexes vary greatly in the degree of ornamentation [5]. Drugs can be attached to a carrier in several ways depending on the requirements of the system. The carrier can act as storage for drug molecules. In such a case, it can take the form of a polymer-drug conjugate or pro-drug to change the release of the compound. Moreover, the physical state of the carrier and the drug attached to it by chemical bonds are essential: (1) water- or organic water-insoluble, reversible, covalently bound; (2) liquid crystalline state at body temperature showing a reversible behavior. They must phase-separate exactly rather than mix molecularly. In the case of organic water-insoluble compounds, they have to mix intimately. More importantly, the driving force for phase separation must be enough to concentrate the drug closer to a membrane compared to the carrier [6].

TYPES OF TARGETING STRATEGIES

The concept of a "targeted" drug delivery encapsulates the idea of sending drugs to a target site and releasing them gradually. The two major strategies through which drugs can be targeted to cells in order to accomplish a biological effect and act inside the body are termed "passive" targeting and "active" targeting. Passive targeting exploits hyperpermeable tissues for drug delivery. Active targeting uses functionalized vesicles that bind to receptors or antigens on specific cells. Peptide ligands, monoclonal antibodies, small molecules, or low pH-sensitive peptides can be used as recognition entities. Folic acid-targeted delivery of doxorubicin to lung cancer cells has been successful. Attaching ligands to vesicles improves drug delivery and reduces side effects. Experimental studies have shown selective interactions with endothelium and breast adenocarcinoma cells. However, intracellular delivery is not guaranteed [7].

NANOPARTICLES IN DRUG DELIVERY

Nanoparticles are single molecules, atoms, or atomic clusters bearing a capacious surface area concerning their volume. It essentially comprises nanopowders fabricated by both unagglomerated and agglomerated systems. The major amplification in nanoparticle research primarily employs two types of nanoparticles, a 'nano-sized product' and the second as a 'nanosized carrier'. It is mainly due to the intricate application and functional programs pertaining to diminution in size. For instance, a metallic nanoparticle with a mean size of circa 100 nm or lesser, had a completely different massive surface area than a norm of some milliliter amounts of its powders. In essence, the major factors favoring the importance of nanoparticles chiefly lie in their inherent, intrinsic, and typical electronic, optical, and magnetic features, to name a few. The prime functional pathways include as a ferrofluid in tapes, toners and copying, recording media in hard discs and high fidelity tapes, Catalyst loadings, pigments, sunscreens, materials for transdermal delivery, removal of toxic heavy inputs from water, ion exchangers, and others [8]. Liposomal nanocarriers are commonly used for drug delivery, but their effectiveness is limited due to low solubility of certain drugs. Compellable nanocarriers are expensive and environmentally unfriendly. Polymeric nanocarriers, including Nanocapsules and Nanospheres, offer alternative solutions. They have various applications and advantages, including versatility and ongoing development [9].

TYPES OF NANOPARTICLES

Nanoparticles in drug delivery: The cure for provisional side effects of therapeutics, i.e., the specter of unwanted side effects, is the use of controlled, sustained, targeted drug delivery systems. Nanoparticle application in drug delivery has revolutionized the field of cancer treatment, where therapeutic agents are accumulated at the targeted site, causing minimum or no toxicity to normal cells. Electrical fields can be precisely designed to create sufficiently high transmembrane potentials. Several benefits of nanoparticles have led to the development of different drugs in an attempt to deliver medications directly to target tissues within the body. By enabling the medication to bypass the destruction pathways, it is transported directly to the site of action [10].

Inorganic nanoparticles, substituted and hetero metal nanostructures (metalloporphyrins), superparamagnetic iron oxides, mesoporous materials for drug delivery, and quantum and lanthanide metal nanoparticles are the possible product types that can be developed in nano reparative drug and drug delivery devices. New drug delivery systems will be developed with improvements in nanotechnology, particularly through the use of nanotechnology drug delivery tools. Lipid (solid lipids, emulsions, solid in

water, nanostructured lipid systems, nanoemulsions, and so on) and polymer nanoparticles (dendrimers, micelles, nanospheres, and nanocapsules) fall into this category [11].

APPLICATIONS OF TARGETED DRUG DELIVERY SYSTEMS

Systems that are using the principles of drug delivery have significant potential for practical applications. Several mechanisms are being used to control and improve the circulation of drugs within the body. Physiochemical barriers of blood supply enable preferential accumulation of drug and chemotherapy. Therefore, there is an increasing interest in targeted drug delivery systems to increase the beneficial index of many drugs. Ideally, the application of nanocarriers for drug delivery should result in an improvement in the therapeutic index as it brings about increased tumor selectivity as well as reduced systemic exposure of healthy tissues to the drug. A significant fraction of current research in the field, therefore, is focused on diagnosing, treating, and preventing cancer [12]. Approaches to cancer diagnosis and detection include molecular imaging and immunoassays. Various modalities are frequently used in these assays, including protein-ligand binding and immune-reactivity. Labeled antibodies and conjugation with reporter moieties are common practices in molecular imaging. Unbound antibodies have been utilized to target circulating antigens and deliver drugs to the brain or other parts of the body. However, barriers in cancers prevent therapeutic drugs from reaching stem cells. Using the same antibody as carrier systems for cytotoxic payload has shown improved therapy benefits. This special issue focuses on macromolecules for drug targeting, design, delivery, and stealth systems [13].

CANCER THERAPY

Nanoparticles are effective for targeted cancer therapy. Recent developments improve outcomes. We focus on Nanocurcumin delivery and selective treatment of various cancers with cisplatin. Ultrafine particles can target anti-cancer agents deep in tumor cells and other immune cells, bypassing immune tolerance issues. Particulate systems decrease toxicity and deliver therapeutics to solid tumor sites. Liposomes, polymers, and micelles are under development and clinical use, including liposomal formulations of doxorubicin. Metal-based nanoparticles are exploring solid, preclinical evidence [14].

CHALLENGES AND FUTURE PERSPECTIVES

5.1. Challenges One of the major challenges for the applications of TDDS, especially for those in nanoscale such as polymeric, lipid, metallic, and polymeric metallic molecule-based nanoparticles, is the toxicity of the used materials for the fabrication of TDDS. Apart from this, several TDDs have no possibility of reaching the target site even after an enormous effort. The nature of the intended organ and the administration route also play a role in providing the efficiency of TDDS. The necessity of bulk-scale production of the TDDS mainly for clinical purposes with a supposed cost-effective has shown it still as an unmet need. Though several advantages are there with the TDDS, the short half-life of them is a major limitation. The cost of fabricating several types of TDDs is more. The selected TDDs must pass through multiple stages for bringing them into the market [15]. Apart from the mentioned issues, advancements in TDDS have made it possible to use a single molecule for area-specific treatment instead of multiple therapies. Research on bioinspired TDDS using PPTT and Nanoshells is progressing, and exploring ligand-receptor approaches can address the issue of biological variability. Encapsulating stem TDDS information for localization and systemic tracking is a future direction. Computational methodologies can be developed to understand cell-specific phenomena. More granular research is needed to bridge the gap between nanomedicine and the clinic. Embolization TDDs with biocompatible carriers can bring about a revolution. Clinical trials with real-time data and a larger sample size are needed to confirm the effectiveness of theranostic drug delivery systems. TDDs offer improved localization and fewer off-target effects. Improved agents can enhance interventional strategies [16].

CONCLUSION

Nanomedicine's advancements in targeted drug delivery systems represent a significant leap forward in the treatment of complex diseases, particularly cancer. The ability of nanoparticles to deliver drugs directly to diseased cells, while minimizing harm to healthy tissues, presents an attractive alternative to traditional therapies. Despite the challenges posed by toxicity, production scalability, and clinical efficacy, the future of TDDS is promising. Research into bioinspired and ligand-receptor approaches, as well as computational models, will likely address current limitations, paving the way for more efficient, personalized treatments that enhance patient outcomes. The ongoing development of nanotechnology holds immense potential for improving therapeutic interventions across various medical fields.

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