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Biocompatible Nanomaterials for Targeted Drug Delivery in Cancer Therapy

William Connor*

Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin, D02 PN40, Ireland

Introduction

Cancer remains one of the leading causes of death worldwide, accounting for nearly 10 million deaths annually, with increasing incidence across all age groups and populations. Traditional cancer treatments—including chemotherapy, radiation, and surgery—while often effective, are accompanied by significant limitations such as systemic toxicity, non-specific drug distribution, poor solubility of therapeutic agents, and development of resistance. These challenges have led researchers to explore advanced, precise, and personalized therapeutic strategies. Among them, nanotechnology has emerged as a transformative approach, especially in the design of targeted drug delivery systems. Nanomaterials, by virtue of their size, surface properties, and functionalizability, offer significant advantages in selectively delivering anticancer agents to tumor sites while sparing healthy tissues. The development of biocompatible nanomaterials—those that do not induce toxic or immune responses—has further enhanced the feasibility of nanomedicine in clinical oncology. These materials are engineered to interact safely with biological systems, degrade or excrete efficiently, and provide controlled and responsive drug release. This paper explores the various types of biocompatible nanomaterials used in cancer therapy, their mechanisms of targeted drug delivery, therapeutic advantages, and the ongoing challenges and prospects in their clinical translation [1].

Description

Biocompatible nanomaterials used for cancer drug delivery span a wide range of classes, including lipid-based nanoparticles, polymeric nanoparticles, dendrimers, inorganic nanoparticles, and biomimetic systems. Liposomes and solid lipid nanoparticles are among the earliest and most clinically validated nanocarriers. Composed of natural or synthetic lipids, these carriers encapsulate hydrophilic drugs in their aqueous core or hydrophobic drugs within their lipid bilayer. Their biocompatibility and ability to fuse with cell membranes make them highly effective for intracellular delivery. For instance, Doxil®, a liposomal formulation of doxorubicin, was one of the first FDA-approved nano-drugs, demonstrating reduced cardiotoxicity compared to free doxorubicin. Polymeric nanoparticles, constructed from biodegradable materials like PLGA (poly(lactic-co-glycolic acid)), PEG (polyethylene glycol), and chitosan, allow controlled drug release and surface functionalization with targeting ligands. These properties ensure that drugs are released specifically at tumor sites over a sustained period, enhancing therapeutic efficacy while minimizing systemic side effects.

Targeting strategies play a crucial role in directing nanocarriers to cancer cells. Passive targeting exploits the Enhanced Permeability and Retention (EPR) effect, a phenomenon where nanoparticles accumulate in tumor tissue due to leaky vasculature and poor lymphatic drainage. However, the variability of the EPR effect across tumor types and patients has driven the development of active targeting mechanisms. These involve modifying nanomaterials with ligands such as antibodies, peptides, aptamers, or small molecules that recognize and bind specifically to overexpressed receptors on cancer cells (e.g., folate receptors, transferrin receptors, HER2). Once bound, the nanocarriers are internalized via receptor-mediated endocytosis, facilitating intracellular drug release. To further enhance targeting specificity, stimuli-responsive nanomaterials have been developed. These smart systems release their payload in response to internal triggers (e.g., pH, enzymes, redox environment) or external stimuli (e.g., temperature, light, magnetic field), ensuring that drugs are delivered precisely when and where they are needed most.

Inorganic nanomaterials such as gold nanoparticles, mesoporous silica nanoparticles, quantum dots, and magnetic nanoparticles offer unique optical, electrical, and magnetic properties that can be exploited for both therapeutic and diagnostic purposes a concept known as theranostics. For example, gold nanoparticles can be conjugated with drugs and targeting ligands while also being used for photothermal therapy, where they convert absorbed light into heat to ablate tumor cells. Magnetic nanoparticles like iron oxide can be directed using external magnetic fields and visualized via Magnetic Resonance Imaging (MRI), allowing for real-time tracking of drug delivery. However, while these materials offer multifunctionality, ensuring their long-term safety and biodegradability is crucial for clinical acceptance. Researchers are increasingly combining inorganic cores with biocompatible shells or coatings (e.g., PEGylation) to improve circulation time and minimize immune recognition [2].

Conclusion

Biocompatible nanomaterials represent a revolutionary approach to cancer therapy, offering unprecedented specificity, controlled release, and reduced systemic toxicity through targeted drug delivery. By leveraging the unique properties of nanoscale materials and engineering them for compatibility with biological systems, scientists have created versatile platforms capable of transforming the oncology landscape. From liposomes and biodegradable polymers to smart inorganic systems and biomimetic vesicles, each class of nanomaterials brings distinct advantages tailored to different therapeutic needs. While the journey from bench to bedside is complex, marked by regulatory, technical, and biological challenges, the progress so far is promising. Continued interdisciplinary collaboration among material scientists, oncologists, pharmacologists, and regulatory agencies will be vital to unlocking the full potential of nanomedicine. Ultimately, the integration of biocompatible nanomaterials into mainstream cancer treatment protocols could significantly enhance treatment efficacy, improve patient quality of life, and bring us closer to the goal of personalized, targeted cancer care.

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Conflict of Interest

None.

***Address for Correspondence:** William Connor, Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin, D02 PN40, Ireland; E-mail: william@connor.ie*

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