

The logo for RADemics, featuring the text "RADemics" in white on a blue arrow-shaped background pointing to the right. The arrow is part of a larger blue horizontal bar that is attached to a dark blue vertical bar on the left side of the page.

RADemics

Role of Nanoparticles in Smart Drug Delivery and Targeted Cancer Therapy

A decorative graphic consisting of several thin, curved lines in shades of blue and grey, originating from the bottom left and extending upwards and to the right, resembling stylized grass or reeds.

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Abstract

Nanoparticle-based drug delivery has emerged as a transformative approach in oncology, enabling precise targeting and improved therapeutic outcomes compared to conventional treatments. Limitations associated with traditional chemotherapy, including non-specific distribution, systemic toxicity, and poor drug stability, have accelerated the development of nanomedicine-driven strategies. This chapter presents a comprehensive analysis of smart and stimuli-responsive nanoparticle systems designed for targeted cancer therapy, emphasizing their physicochemical properties, cellular uptake mechanisms, and controlled intracellular drug release. Diverse nanocarriers, including lipid-based, polymeric, metallic, and carbon-based systems, are examined in relation to their targeting efficiency and multifunctional capabilities. Particular focus is given to dual and multi-targeting strategies, tumor microenvironment responsiveness, and theranostic applications that integrate diagnosis with therapy. Critical challenges involving biocompatibility, toxicity, and clinical translation are also addressed alongside emerging advancements in precision nanomedicine.

Keywords: Nanoparticles, Targeted Drug Delivery, Cancer Therapy, Smart Nanocarriers, Stimuli-Responsive Systems, Nanomedicine.

Introduction

Cancer continues to represent a major global health burden, characterized by uncontrolled cellular proliferation, genetic alterations, and the capacity of malignant cells to invade surrounding tissues and spread to distant organs [1]. Conventional therapeutic strategies such as chemotherapy, radiotherapy, and surgical interventions remain central to cancer management. Clinical limitations associated with these approaches include non-specific drug distribution, dose-limiting toxicity, multidrug resistance, and inadequate drug accumulation within tumor tissues [2]. Chemotherapeutic agents often circulate throughout the body, affecting both cancerous and healthy cells, which results in severe adverse effects and reduced therapeutic efficiency. Rapid degradation of drugs in physiological environments further limits bioavailability and compromises treatment outcomes [3]. Increasing complexity of tumor biology, including heterogeneity in cellular composition and variations in tumor microenvironment, creates additional challenges in achieving precise and effective treatment. Continuous advancements in biomedical research have therefore focused on developing innovative strategies capable of enhancing drug targeting, improving pharmacokinetics, and minimizing systemic toxicity [4]. Nanotechnology has gained

significant attention as a promising solution for addressing these limitations by enabling the design of nanoscale delivery systems that can transport therapeutic agents directly to diseased tissues. Development of such advanced platforms represents a critical step toward improving the safety and effectiveness of cancer therapy while reducing the burden associated with conventional treatment modalities [5].

Nanotechnology provides a powerful framework for engineering materials at the nanoscale, typically within a size range of 1–100 nanometers, where unique physicochemical properties emerge [6]. Materials at this scale exhibit increased surface area, enhanced reactivity, and tunable structural features that facilitate interaction with biological systems [7]. Nanoparticles designed for drug delivery serve as carriers capable of encapsulating therapeutic agents, protecting them from degradation, and enabling controlled release within specific biological environments. Improved solubility of hydrophobic drugs represents a significant advantage offered by nanoparticle-based systems, addressing one of the major challenges in pharmaceutical development [8]. Surface modification techniques allow attachment of functional groups, polymers, or targeting ligands, which enhance stability and promote selective interaction with cellular receptors. Circulation time within the bloodstream can be extended through strategies that reduce recognition by the immune system, thereby improving the probability of nanoparticle accumulation at tumor sites [9]. Structural diversity among nanoparticles, including lipid-based, polymeric, metallic, and carbon-based systems, supports a wide range of applications in oncology. Integration of these nanoscale materials within drug delivery systems has led to the emergence of nanomedicine as an interdisciplinary field that combines principles of chemistry, biology, and engineering to improve therapeutic outcomes in cancer treatment [10].