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Advancements in Nanotechnology for Drug Delivery in Coronary Artery Disease: Enhancing Efficacy and Minimizing Side Effects

Annie Marques*

Department of Cardiology, University of Toronto, 27 King's College Cir, Toronto, ON M5S 1A1, Canada

Abstract

Coronary artery disease remains a leading cause of mortality and morbidity worldwide. The conventional treatment approaches often face limitations such as low drug bioavailability, off-target effects and inadequate therapeutic outcomes. Nanotechnology has emerged as a promising solution to address these challenges by enabling targeted drug delivery to the affected site, thereby enhancing therapeutic efficacy while minimizing systemic side effects. This article reviews recent advancements in nanotechnology-based drug delivery systems for CAD treatment, highlighting the strategies to improve drug selectivity, stability and controlled release. Furthermore, the potential benefits and challenges of these novel approaches are discussed, along with their potential to revolutionize the management of CAD.

Keywords: Coronary heart disease • Theranostic nanoparticles • Nanostructured lipid carriers

Introduction

Coronary artery disease is a prevalent cardiovascular disorder characterized by the narrowing or blockage of coronary arteries, leading to inadequate blood supply to the heart muscle. Traditional therapies often involve systemic drug administration, which results in suboptimal drug concentration at the target site and potential side effects due to off-target effects. Nanotechnology-based drug delivery systems have emerged as a transformative approach to enhance therapeutic outcomes by allowing precise control over drug release kinetics, bioavailability and tissue targeting. The field of nanotechnology has witnessed remarkable progress in the development of nanoparticles as versatile carriers for targeted drug delivery in the context of coronary artery disease. Nanoparticles, due to their unique properties and tunability, offer a promising avenue to overcome the limitations of traditional drug delivery methods. This section explores the diverse range of nanoparticles that have been harnessed for CAD treatment, highlighting their potential to enhance therapeutic efficacy while minimizing off-target effects.

Liposomes, polymeric nanoparticles and lipid nanoparticles are among the most extensively studied nanoparticle types for targeted drug delivery in CAD. Liposomes, lipid bilayer vesicles, are particularly attractive due to their biocompatibility, versatility and ability to encapsulate both hydrophilic and hydrophobic drugs. Polymeric nanoparticles, often composed of biodegradable polymers, allow for controlled drug release and sustained therapeutic effect. Lipid nanoparticles, including solid lipid nanoparticles and nanostructured lipid carriers, exhibit improved drug stability and controlled release profiles [1-3].

Literature Review

Nanoparticles leverage the enhanced permeability and retention effect, a hallmark of tumor vasculature, for passive targeting to CAD lesions. In CAD, inflammatory processes lead to alterations in vascular permeability, thereby enabling nanoparticles to accumulate preferentially at the diseased sites. This phenomenon allows for enhanced drug delivery to areas of active inflammation, reducing drug exposure to healthy tissues and mitigating systemic side effects. To further enhance drug specificity, nanoparticles can be functionalized with ligands that recognize biomarkers overexpressed in CAD-affected regions. Surface modification with antibodies, peptides, aptamers, or small molecules enables active targeting, enhancing nanoparticle uptake at the target site. This strategy not only improves drug concentration at the lesion but also facilitates cellular internalization, potentially enhancing therapeutic outcomes [4,5].

Beyond drug delivery, theranostic nanoparticles integrate diagnostic and therapeutic functionalities, enabling real-time monitoring of treatment efficacy. These nanoparticles incorporate imaging agents such as contrast agents, fluorescent dyes, or magnetic nanoparticles, allowing non-invasive assessment of disease progression and response to treatment. This dual-purpose approach paves the way for personalized medicine strategies, as treatment plans can be adjusted based on real-time imaging data.

Discussion

Challenges and future directions

While the potential of nanoparticles for targeted drug delivery in CAD is promising, challenges remain. Achieving optimal drug loading efficiency, ensuring stable nanoparticle formulations and addressing potential immunogenicity concerns are ongoing research areas. Additionally, the translation of nanoparticle-based therapies from preclinical studies to clinical practice requires meticulous validation of safety, efficacy and scalability.

Localized drug delivery devices, such as drug-eluting stents, have revolutionized CAD treatment. Incorporating nanotechnology, DES can provide controlled and sustained release of drugs directly to the coronary lesion site, minimizing restenosis and promoting vascular healing.

Theranostic nanoparticles

Theranostic nanoparticles combine therapeutic and diagnostic functions, enabling real-time monitoring of treatment efficacy. By incorporating imaging agents, these nanoparticles allow non-invasive assessment of the disease progression and response to treatment, thus guiding personalized therapy. The success of nanotechnology-based drug delivery systems for treating coronary artery disease hinges on their ability to surmount various biological barriers that can impede efficient drug transport and therapeutic efficacy. This section

***Address for Correspondence:** Annie Marques, Department of Cardiology, University of Toronto, 27 King's College Cir, Toronto, ON M5S 1A1, Canada, E-mail: anniemarques21@gmail.com*

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delves into the strategies and advancements in nanotechnology that have been developed to overcome these barriers, ensuring that therapeutic agents reach their intended targets within the cardiovascular system.

The blood-brain barrier poses a significant challenge for delivering therapeutic agents to the central nervous system, including CAD-related neural complications. Nanoparticles have emerged as potential solutions due to their ability to transport drugs across the BBB. Surface modifications and functionalization with receptor-targeting ligands enable nanoparticles to traverse the BBB via receptor-mediated endocytosis or transcytosis. Techniques like focused ultrasound in combination with nanoparticles can further enhance BBB permeability, allowing for precise drug delivery to CAD-associated brain regions.

Multidrug resistance, often observed in CAD patients undergoing long-term therapy, can hamper the efficacy of drug treatments. Nanoparticles have been engineered to overcome MDR by exploiting their unique properties. For instance, drug encapsulation within nanoparticles can shield the therapeutic agent from efflux pumps responsible for drug expulsion. Moreover, stimuli-responsive nanoparticles can release drugs selectively in the presence of specific intracellular triggers, evading MDR mechanisms and enhancing drug retention within target cells.

Nanoparticles encounter barriers posed by the endothelial lining of blood vessels when aiming to reach specific coronary lesions. These barriers include tight junctions between endothelial cells that limit drug transport. By leveraging the EPR effect, nanoparticles can exploit the increased permeability of the inflamed endothelium associated with CAD. Surface engineering of nanoparticles with ligands that interact with endothelial cell adhesion molecules enhances their adhesion and transmigration across the endothelial barrier, facilitating targeted drug delivery. Nanoparticles offer precise control over drug release kinetics, minimizing burst release and ensuring sustained therapeutic concentrations. This controlled release is crucial for drugs with narrow therapeutic windows or those requiring prolonged action [6].

The safety and biocompatibility of nanomaterials are essential considerations. Recent advancements in nanotoxicology have improved our understanding of potential risks, aiding in the design of nanoparticles with minimal adverse effects. Several nanotechnology-based drug delivery systems have shown promise in preclinical studies. However, successful clinical translation requires rigorous evaluation of safety, efficacy and scalability. Future research should focus on large-scale clinical trials, personalized therapy approaches and the integration of nanotechnology with other emerging therapies.

Conclusion

Nanotechnology-based drug delivery systems hold tremendous potential for revolutionizing CAD treatment. These advancements enable targeted drug delivery, improved therapeutic outcomes and reduced side effects. As research progresses, a deeper understanding of the complex interactions between nanoparticles and biological systems will pave the way for innovative solutions in the management of CAD.

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Conflict of Interest

Authors declare no conflict of interest.

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