

Overview of Recent Advancement of Nanostent in Pharmaceutical Application

Abdul Razak Mohamed Sikkander*

Abstract

Interventional cardiology has witnessed remarkable progress with the evolution of nanotechnology, leading to the development of nanostents. Nanostents, characterized by their nanoscale features and innovative materials, have emerged as a cutting-edge solution for addressing the limitations associated with traditional stent technologies. This thorough analysis examines the most recent developments in the design, manufacture, and use of nanostents, emphasizing how they may completely transform vascular interventions. The first section of the review provides an overview of the nanomaterials employed in nanostent construction, including biocompatible polymers, advanced alloys, and bioresorbable elements. These materials contribute to enhanced biocompatibility, reduced inflammation, and improved long-term outcomes. The incorporation of nanoscale surface modifications further optimizes the interaction between the nanostent and the vascular environment, promoting quicker endothelialization and minimizing the risk of restenosis. The second part of the review delves into the engineering innovations that have enabled the development of smart nanostents. These devices are equipped with sensors and actuators, allowing for real-time monitoring of vascular conditions and responsive adjustments to optimize therapeutic outcomes. Additionally, the integration of nanotechnology enables precise drug delivery strategies, ensuring targeted and controlled release of pharmaceutical agents to the site of intervention. Clinical studies and preclinical experiments supporting the efficacy and safety of nanostents are systematically reviewed in the third section. Comparative analyses with conventional stents reveal promising results, showcasing the potential of nanostents in reducing complications, such as thrombosis and restenosis while improving patient outcomes.

Keywords: Nanoscale, blocked artery, microfabrication techniques, anti-proliferative drugs, anti-proliferative drugs

INTRODUCTION

Nanotechnology is being actively explored in stent development to improve the performance, biocompatibility, and therapeutic capabilities of these medical devices [1]. Nanotechnology enables the development of drug-eluting stents with precise control over the release of therapeutic agents [2]. This is crucial for preventing restenosis and reducing the risk of complications. Nanomaterials can be used

to modify stent surfaces, improving biocompatibility, and reducing the risk of adverse reactions or inflammation when the stent is implanted. Nanotechnology allows for the creation of bioresorbable stents [3–19]. Over time, these stents gradually dissolve, removing the foreign material's long-term presence in the body. Precision Medicine: Nanotechnology facilitates targeted drug delivery to specific cells or tissues, enhancing the therapeutic effect while minimizing side effects on surrounding healthy tissues. Incorporating nanomaterials with imaging properties into stents

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Received Date: March 07, 2024
Accepted Date: March 29, 2024
Published Date: April 30, 2024

Citation: Abdul Razak Mohamed Sikkander. Overview of Recent Advancement of Nano Stent in Pharmaceutical Application. Trends in Drug Delivery. 2024; 11(1): 22–43p.

can enhance their visibility during medical imaging procedures, aiding in accurate diagnosis and monitoring. Nanomaterials can be engineered to have anti-inflammatory properties, potentially minimizing the inflammatory response triggered by the presence of a stent in the body. By manipulating materials at the nanoscale, nanotechnology can create stents with increased mechanical strength, flexibility, and durability. Integrating nanoscale sensors or probes into stents may enable the early detection of restenosis or other complications, allowing for timely intervention [20]. Nanotechnology enables the development of theragnostic stents that integrate both therapeutic and diagnostic functionalities, providing a comprehensive approach to patient care. Research in these areas aims to address challenges associated with traditional stent technologies, such as restenosis and inflammation, while also exploring new possibilities for personalized and targeted medical interventions. It is important to note that while these concepts show promise, their clinical applicability requires rigorous testing and validation through preclinical and clinical studies [21–34] (Table 1).

RESEARCH AND METHODOLOGIES

Research methodologies for studying nanostents involve a combination of experimental techniques, characterization methods, and analytical approaches (Figure 1).

Nanostents are devices designed at the nanoscale to treat or prevent the blockage of blood vessels. Conduct a comprehensive review of existing literature to understand the current state of nanostent research, including materials, design, fabrication methods, and performance evaluations [35–48]. Nanostents are a promising alternative in the medical device industry because they have a number of advantages over traditional stents.

Table 1. Comparative study of nanostents involves the systematic evaluation of these advanced stents against conventional stents, aiming to elucidate differences in efficacy, safety, and overall clinical performance.

S.N.	Content	Observation and inference
1	Restenosis rates	Evaluate and compare rates of restenosis between nanostents and conventional stents. Analyze data from imaging modalities (e.g., angiography, intravascular ultrasound) to assess vessel patency and the extent of restenosis.
2	Thrombosis incidence	Investigate the occurrence of stent thrombosis in patients with nanostents compared to those with conventional stents. Assess the thrombotic risk at various time points post-implantation.
3	Biocompatibility	Examine tissue responses and biocompatibility by analyzing inflammatory markers and histological data. Assess endothelialization and neointimal formation surrounding stent struts.
4	Drug-eluting capabilities	Explore the drug-eluting capabilities of nanostents in comparison to traditional drug-eluting stents. Evaluate the release kinetics and distribution of therapeutic agents.
5	Long-term Clinical Outcomes	Investigate and compare long-term clinical outcomes, including major adverse cardiac events (MACE), target lesion revascularization, and patient survival rates. Analyze data from extended follow-up periods to capture late complications.
6	Vascular healing	Assess the impact of nanostents on vascular healing by examining neointimal coverage and late luminal loss. Utilize imaging modalities to study vessel remodeling and healing dynamics.
7	Patient subgroup analyses	Conduct subgroup analyses based on patient characteristics (e.g., diabetes, multi-vessel disease) to identify potential variations in outcomes. Evaluate the performance of nanostents in specific patient populations.
8	Cost-effectiveness	Explore the economic aspects of nanostents by comparing their cost-effectiveness with traditional stents. Consider factors such as the need for revascularization procedures and associated healthcare costs.
9	Regulatory considerations	Address regulatory considerations and compliance with standards in the regions where the studies are conducted. Evaluate the feasibility of adopting nanostents in routine clinical practice.
10	Meta-analyses and systematic reviews	Conduct meta-analyses or systematic reviews to synthesize data from multiple comparative studies, providing a broader perspective on the overall evidence.

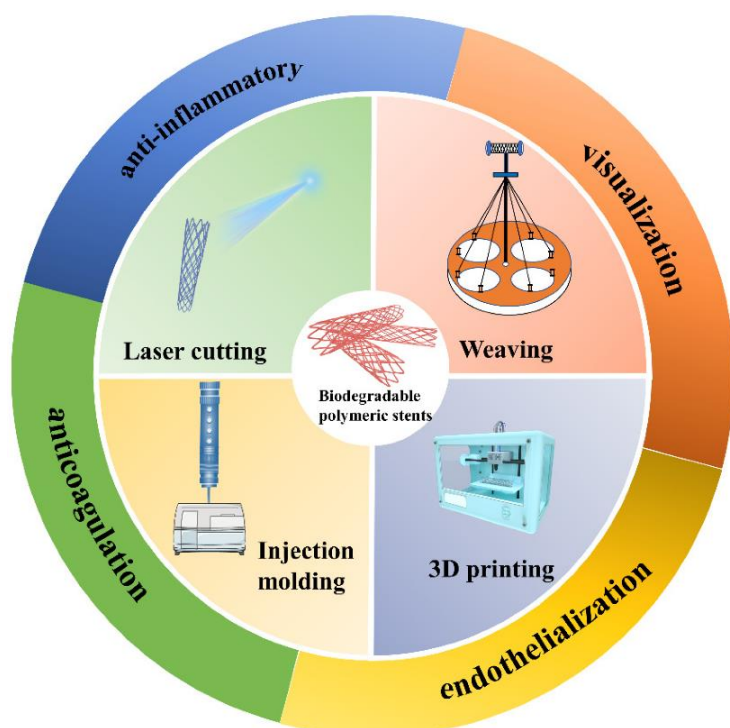


Figure 1. Biodegradable polymeric stents.

Dimensions and composition: Nanostents have a substantially smaller footprint than traditional stents. Because of their nanoscale size, they can be inserted into intricate blood vessels with greater flexibility and less chance of damaging the vessel wall.

Biocompatibility: Biocompatible materials, such as biodegradable polymers or metals like gold or platinum, are frequently used to create nanostents. Compared to conventional stents, which might be composed of less biocompatible materials, this lowers the chance of negative reactions or inflammatory responses within the body.

Drug delivery: To prevent restenosis (re-narrowing of the blood vessel), drugs can be incorporated into nanostent designs through the use of drug-eluting capabilities, which release the drugs gradually over time. Compared to the systemic drug administration found in traditional stents, this targeted drug delivery is more efficient.

Better healing: When compared to traditional stents, nanostents have the potential to improve tissue healing. Their surface characteristics and smaller size can encourage the growth of endothelial cells, which cover the stent naturally and lower the chance of clot formation.

Decreased risk of thrombosis: When compared to traditional stents, nanostents may lower the risk of thrombosis (blood clotting). Their enhanced biocompatibility and reduced size reduce the possibility of clot formation and platelet adhesion on the stent surface.

High precision in the engineering of nanostents makes it possible to better customize them to fit the unique anatomy of each blood vessel. Compared to conventional stents, which might have a more standardized design, this can result in better outcomes and fewer complications. Although nanostents have many benefits, research, and development are still being done on them, and it is unknown how safe and effective they will be in the long run—in comparison to conventional stents. Nonetheless, because of their special qualities, nanostents hold great promise as a medical technology for vascular surgery and interventional cardiology (Figure 2).

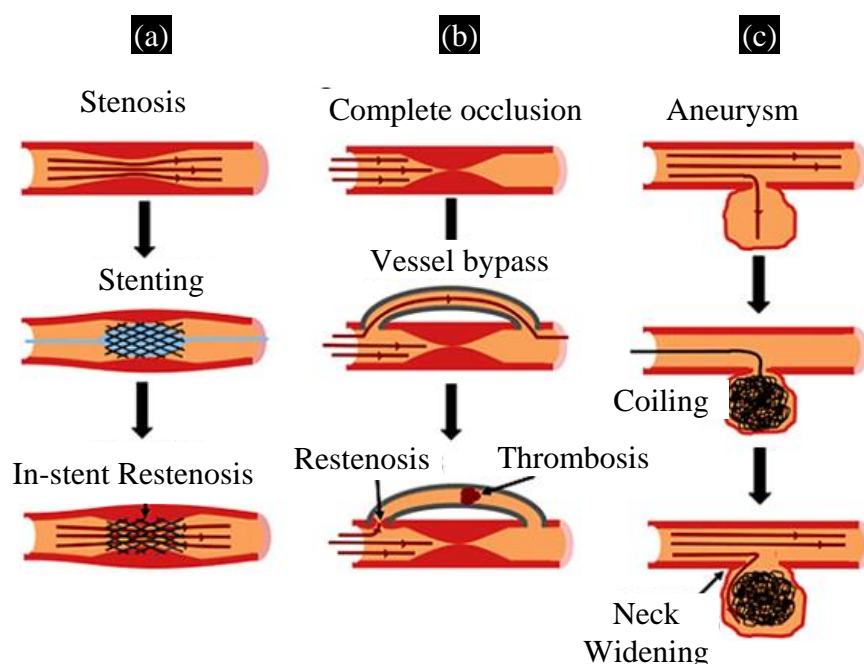


Figure 2. Targeted delivery of bioactive molecules for vascular intervention and tissue engineering.

Choose appropriate nanomaterials for constructing the stent. Take into account the mechanical characteristics, biocompatibility, and integration potential of the biological environment. Investigate and choose suitable fabrication methods for nanostents, such as electrospinning, layer-by-layer assembly, or microfabrication techniques. Employ techniques such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), and atomic force microscopy (AFM) to characterize the structure, morphology, and composition of the nanomaterials [49, 50]. Perform *in vitro* studies to assess the behavior of nanostents in controlled laboratory environments. This may include cell culture experiments to evaluate cytocompatibility, adhesion, and proliferation. Conduct animal studies to evaluate the biocompatibility, efficacy, and safety of nanostents within living organisms. Assess factors such as tissue response, inflammation, and long-term performance [51, 52]. If the nanostent has drug delivery capabilities, research the drug's release kinetics. To measure drug concentrations over time, use methods such as high-performance liquid chromatography (HPLC). Evaluate the mechanical properties of the nanostent, including tensile strength, flexibility, and radial strength. This is crucial to ensure the stent can withstand physiological conditions. Assess the biological response to the nanostent, including inflammation, thrombogenicity, and the activation of the immune system. Utilize medical imaging techniques such as angiography, magnetic resonance imaging (MRI), or computed tomography (CT) to visualize the deployment and performance of the nanostent *in vivo*. Employ statistical methods to analyze the data obtained from experiments, ensuring the reliability and significance of the results. Conduct studies to assess the long-term durability and stability of the nanostent under physiological conditions [53–66]. By combining these research methodologies, scientists and researchers can gain a comprehensive understanding of the performance, safety, and efficacy of nanostents, ultimately contributing to the development of improved medical devices for cardiovascular applications (Figure 3).

DRUG-ELUTING NANOSTENTS

Drug delivery can be precisely controlled thanks to nanotechnology. To prevent restenosis more successfully, drug-eluting nanostents may contain nanomaterials to regulate the release of therapeutic agents, such as anti-proliferative medications. Drug-eluting nanostents represent an innovative approach to addressing restenosis and improving the effectiveness of vascular interventions [67] (Figure 4).

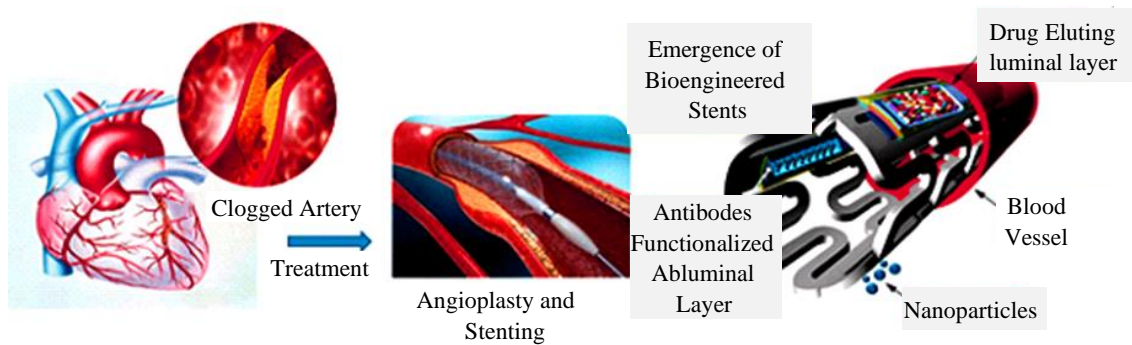


Figure 3. Angioplasty and stenting.

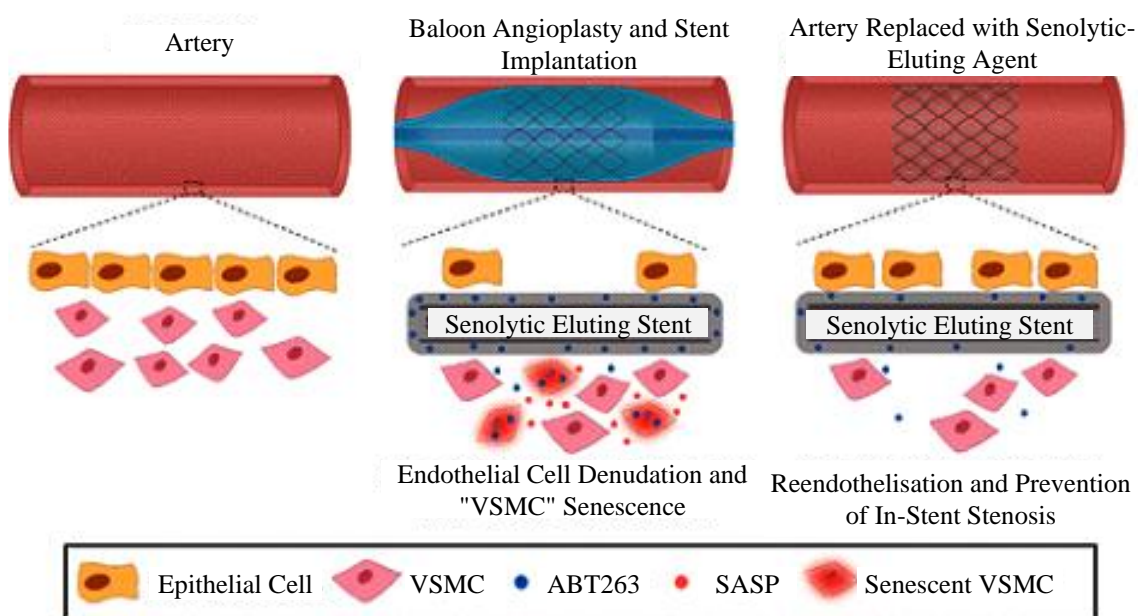


Figure 4. Drug-eluting nanostents.

Nanotechnology enables the precise control of drug release from stents. By using nanomaterials, the release of therapeutic agents can be finely tuned, allowing for a sustained and controlled delivery over time [68]. Drug-eluting stents often incorporate anti-proliferative drugs. These drugs aim to inhibit the excessive growth of smooth muscle cells in the arterial wall, which is a common cause of restenosis after stent implantation [69]. The re-narrowing of a blood vessel following an initially successful stent implantation is known as restenosis. Drug-eluting nanostents are designed to release medications in a localized manner, preventing the proliferation of cells that could lead to restenosis [70]. Drugs can be specifically delivered to their site of action thanks to the application of nanotechnology. By minimizing systemic exposure, this focused strategy lowers the chance of side effects in other parts of the body [71]. Nanomaterials used in these stents can be engineered for enhanced biocompatibility. This is crucial to guarantee that neither the drug delivery mechanism nor the stent will cause an immunological reaction or other negative side effects in the body [72]. Different drugs may be suitable for preventing restenosis in various patients. The ability to customize the drug payload in nanotechnology-based stents allows for tailored treatment approaches based on individual patient needs [73]. The controlled release of therapeutic agents directly at the stent site contributes to more effective treatment, potentially leading to improved patient outcomes with reduced instances of restenosis and related complications [74]. While drug-eluting stents have been successful in reducing restenosis rates compared to bare-metal stents, ongoing research aims to further optimize drug delivery systems using nanotechnology. This includes exploring new drug formulations, coatings, and nanomaterial designs to enhance the efficacy

and safety of these innovative medical devices. It is important to note that advancements in this field are subject to ongoing research, clinical trials, and regulatory approvals [75].

Drug-eluting nanostents are an innovative advancement in the medical device industry. By utilizing drug delivery technologies and nanotechnology, these stents are intended to overcome certain of the drawbacks of conventional stents. Please note that developments may have occurred since then, and it is advisable to check the latest literature for the most recent information (Table 2).

BIORESORBABLE NANOSTENTS

Some researchers are investigating bioresorbable stents at the nanoscale. The purpose of these stents is to reduce the long-term presence of foreign material in the body by gradually dissolving over time. Bioresorbable nanostents represent a notable development in stent technology. The goal of bioresorbable stents is to provide temporary support to a blood vessel or other tubular structures and then gradually dissolve, eliminating the need for a permanent implant [76–105] (Figure 5).

Table 2. Recent trends, advancements, and drawbacks of drug-eluting nanostents.

S.N.	Content	Recent Trends and Advancements	Drawbacks and Challenges
1	Drug Delivery Systems	Nanostents utilize advanced drug delivery systems, often involving nanoparticles, to release therapeutic agents over time. This controlled release helps to prevent restenosis (the re-narrowing of blood vessels) and inflammation.	Despite advancements, ensuring complete biocompatibility and minimizing potential immune reactions remains a challenge. The body's response to the stent materials and the released drugs is an ongoing area of research.
2	Biocompatible Materials	Advances in nanotechnology have led to the development of biocompatible materials for nanostents. These materials aim to minimize adverse reactions within the body and promote better integration with the surrounding tissues.	The long-term safety and durability of drug-eluting nanostents need thorough investigation. Studies and ongoing observation are necessary to evaluate any possible negative effects over a long time.
3	Targeted Drug Delivery	Nanostents allow for targeted drug delivery, ensuring that the therapeutic agents are delivered specifically to the affected area. By doing this, the treatment's efficacy is increased and adverse effects on healthy tissues are reduced.	The development and manufacturing of nanostents, especially those incorporating advanced technologies, may be cost-prohibitive. This can limit widespread adoption, particularly in regions with limited healthcare resources.
4	Reduced Inflammation and Restenosis	Drug-eluting nanostents aim to reduce inflammation and the risk of restenosis, which are common issues with traditional stents.	To address these issues, the application of nanotechnology enables a more targeted and continuous release of medications.
5	Improved Imaging Technologies	Integration with advanced imaging technologies, such as intravascular ultrasound (IVUS) or optical coherence tomography (OCT), allows for better visualization and placement of nanostents, improving the overall success of the procedure.	Meeting regulatory requirements for approval and ensuring the safety and efficacy of nanostents can be a complex process, adding to the time and cost of bringing these devices to market.
6	Improved Imaging Technologies	Integration with advanced imaging technologies, such as intravascular ultrasound (IVUS) or optical coherence tomography (OCT), allows for better visualization and placement of nanostents, improving the overall success of the procedure.	Complexity in Manufacturing: The manufacturing processes for nanostents can be intricate, requiring precision and quality control. Achieving consistency in production while maintaining the desired properties poses a challenge. It is important to note that research and development in the field of medical devices, including drug-eluting nanostents, are dynamic, and new findings may have emerged since my last update. Always consult the latest scientific literature and medical sources for the most current information on this topic.

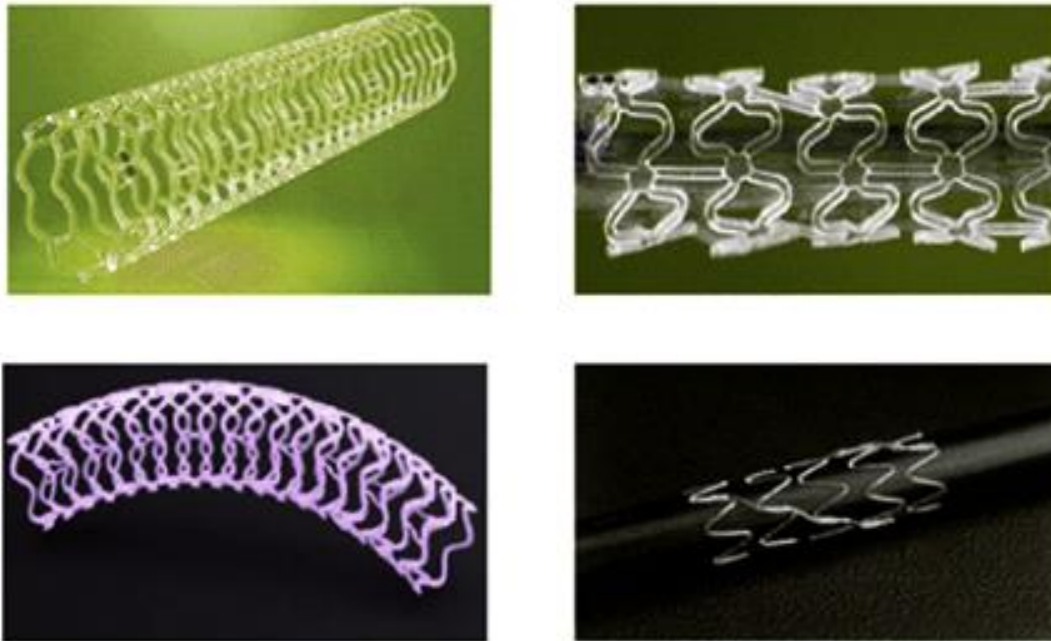


Figure 5. Bioresorbable nanostent.

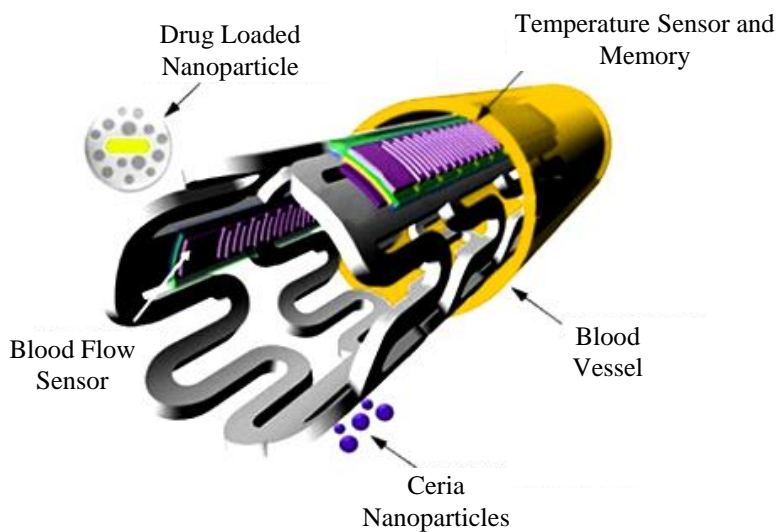


Figure 6. Bioresorbable stents are designed to break down over time, eventually being absorbed by the body.

Bioresorbable stents are designed to break down over time, eventually being absorbed by the body. At the nanoscale, the materials used for these stents can be engineered to degrade into biocompatible byproducts that are easily absorbed or excreted [106] (Figure 6).

The initial purpose of a bioresorbable nanostent is to provide temporary structural support to a vessel or duct, such as an artery. This support is crucial during the initial healing phase when the vessel is at risk of collapsing or becoming blocked [107–123]. The precise control of material degradation rate is made possible by nanotechnology. This enables stents to be designed to degrade gradually, aligning with the natural healing process of the body [124]. Bioresorbable nanostents are meant to dissolve entirely, in contrast to conventional stents, which stay in the body indefinitely. This removes the foreign material from the body permanently, which may lower the risk of complications and restore more normal vessel function [125]. In-stent restenosis or thrombosis are examples of late complications that

are occasionally linked to permanent stents. Bioresorbable stents aim to minimize these risks by providing temporary support during the critical healing period and then disappearing [126]. Nanomaterials used in bioresorbable stents can be selected or engineered for optimal biocompatibility. This is crucial to ensure that the degradation process and byproducts do not trigger an inflammatory response or adverse reactions [127]. The use of nanotechnology allows for customization of the bioresorbable stent properties, including degradation kinetics and mechanical strength, to match the specific needs of different patients and clinical scenarios. The medical community is still actively exploring bioresorbable stent research and development, particularly at the nanoscale. Clinical studies and regulatory approvals are essential steps to demonstrate the safety and efficacy of these innovative devices in various medical applications [128].

Bioresorbable nanostents have been an area of active research and development within the field of interventional cardiology. These stents are designed to gradually dissolve within the body after fulfilling their purpose, offering potential advantages over permanent stents (Table 3).

Table 3. Recent trends, advancements, and drawbacks of bioresorbable nanostents.

S.N.	Content	Recent trends and advancements	Drawbacks and challenges
1	Biodegradable materials	Bioresorbable nanostents are typically made from biodegradable materials, often polymers such as polylactic acid (PLA) or polyglycolic acid (PGA). More recently, more biocompatible materials have been developed as a result of advances in material science.	<i>Mechanical Integrity:</i> Maintaining mechanical integrity during the degradation process is a significant challenge. Ensuring that the stent provides adequate support to the vessel during the healing period while gradually resorbing is crucial for successful outcomes.
2	Improved drug delivery	Similar to drug-eluting stents, bioresorbable nanostents can incorporate drug delivery systems to release therapeutic agents gradually. This feature aims to address issues such as inflammation and restenosis during the healing process.	In certain situations, the breakdown products of bioresorbable stents can cause an inflammatory reaction. Balancing the rate of degradation with the body's healing processes is essential to minimize inflammation and potential complications.
3	Gradual degradation	Nano-sized components enable a more controlled and gradual degradation of the stent. This controlled resorption is crucial for maintaining vessel patency and reducing the risk of complications associated with abrupt changes in stent structure.	The long-term safety and durability of bioresorbable stents, especially in real-world, diverse patient populations, remain areas of ongoing research. Ensuring that the stents effectively treat the target condition without causing unforeseen issues is critical.
4	Enhanced imaging technologies	Optical coherence tomography (OCT) and intravascular ultrasound (IVUS) are two examples of advanced imaging technologies that can be integrated to improve procedural outcomes by precisely placing and monitoring bioresorbable nanostents.	Clinical studies evaluating the outcomes of patients treated with bioresorbable stents have shown mixed results. Striking the right balance between stent resorption and vessel support is challenging, and more evidence is needed to establish their efficacy compared to traditional stents.
5	Customization and flexibility	Nanoscale manufacturing techniques enable greater customization and flexibility in the design of bioresorbable stents. Tailoring stent properties to individual patient needs is a trend that enhances the effectiveness of the intervention.	Bioresorbable stents may be more expensive to manufacture than permanent stents. Cost considerations and accessibility can impact the widespread adoption of these advanced technologies, especially in regions with limited healthcare resources. It is important to note that the field of bioresorbable stents is dynamic, and ongoing research may have addressed or identified new challenges since my last update. Always consult the latest scientific literature and medical sources for the most current information on this topic.

SURFACE-MODIFIED NANOSTENTS

Nanotechnology enables the modification of stent surfaces at the nanoscale. This can lower the possibility of negative reactions, increase biocompatibility, and improve the mechanical qualities of the stent. Surface-modified nanostents involve the use of nanotechnology to alter the surface properties of stents at the nanoscale. These modifications aim to improve the stent's performance, biocompatibility, and interaction with the surrounding tissues [129] (Figure 7).

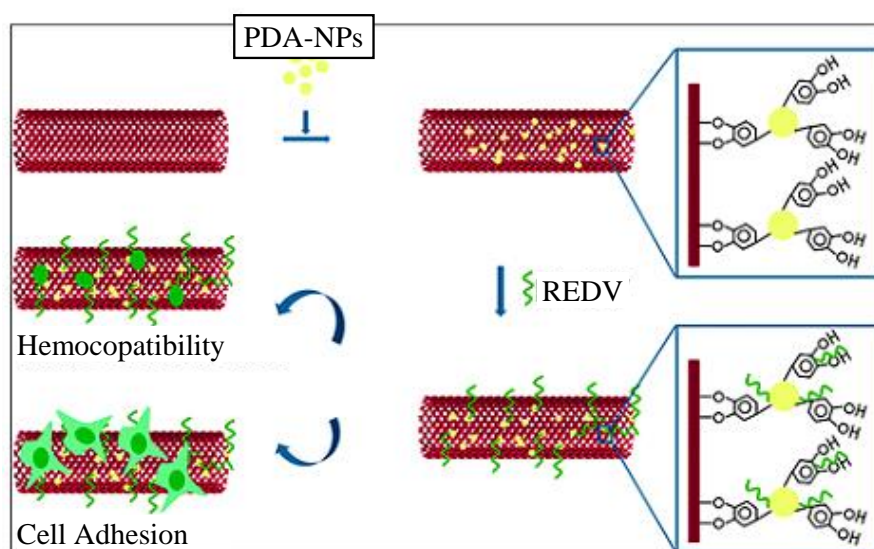


Figure 7. Polydopamine surface-modified nanostent.

Nanotechnology allows for the modification of stent surfaces to enhance biocompatibility. This is crucial to reduce the risk of adverse reactions, inflammation, or immune responses when the stent is implanted [130]. Surface modifications at the nanoscale can be designed to reduce the tendency of stents to promote blood clot formation (thrombosis). Preventing complications like stent thrombosis is crucial [131]. Nanomaterials can be incorporated into coatings that have anti-inflammatory properties. This helps minimize the inflammatory response triggered by the presence of the stent in the body [132]. Nanotechnology enables the incorporation of antimicrobial agents into the stent surface. This is particularly relevant to reduce the risk of infections associated with the implantation of medical devices [133]. Coatings that release medication or therapeutic agents can be made using nanomaterials. These drugs can target specific cellular responses, such as inflammation or cell proliferation, contributing to better outcomes after stent placement [134]. Surface modifications can be designed to improve the interaction between the stent surface and blood components, enhancing hemocompatibility and minimizing the risk of clot formation [135]. Nanotechnology allows for the customization of stent surface properties. This includes tailoring the surface chemistry, roughness, and other characteristics to suit specific medical applications or patient needs [136]. Surface-modified nanostents can contribute to preventing restenosis by influencing the interaction between the stent and the arterial wall. This may involve coatings that inhibit smooth muscle cell proliferation [137]. Surface alterations may facilitate the stent's better integration with the surrounding tissues, which may lessen complications and enhance the device's long-term functionality. Surface-modified nanostents represent a promising avenue for enhancing the capabilities of stents in various medical applications. It is important to conduct thorough preclinical and clinical testing to validate the safety and efficacy of these modifications before widespread clinical use [138].

Surface-modified nanostents have been an area of ongoing research within the field of medical devices. These stents are designed with surface modifications at the nanoscale to enhance their performance, biocompatibility, and drug delivery capabilities (Table 4).

Table 4. Recent trends, advancements, and drawbacks of surface-modified nanostents.

S.N.	Content	Recent trends and advancements	Drawbacks and challenges
1	Nanoscale Surface Coatings	Surface modifications at the nanoscale involve the application of coatings or layers of materials to the stent surface. These coatings can decrease inflammation, increase drug delivery, and make the stent more biocompatible.	Ensuring the durability and longevity of nanoscale surface modifications is a challenge. The stent must maintain its modified properties over time to provide sustained benefits without compromising structural integrity.
2	Drug-Eluting Capabilities	Many surface-modified nanostents are designed to incorporate drug-eluting capabilities. The nanoscale modifications allow for precise control over drug release, helping to prevent restenosis and inflammation more effectively.	While surface modifications aim to improve biocompatibility, unforeseen immune reactions or adverse responses to the modified surfaces may occur. Comprehensive biocompatibility assessments are crucial to address these concerns.
3	Improved Hemocompatibility	Nanoscale surface modifications can enhance the hemocompatibility of stents, reducing the risk of thrombosis and promoting better integration with the vascular tissue.	The manufacturing of surface-modified nanostents can be complex and may require precise control over nanoscale features. Achieving consistency in the production process while maintaining the desired surface properties poses a challenge.
4	Biodegradable Surface Coatings	Some advancements involve the development of biodegradable nanoscale coatings. These coatings gradually degrade over time, allowing for a controlled release of drugs and minimizing the long-term presence of foreign materials within the body.	Meeting regulatory requirements for the approval of surface-modified nanostents can be challenging. The unique features of these stents may require additional scrutiny to ensure safety and efficacy before widespread clinical use.
5	Targeted Delivery Systems	Surface-modified nanostents enable targeted drug delivery to specific areas of the blood vessel, improving the therapeutic effects while minimizing potential side effects on surrounding tissues.	The incorporation of advanced surface modifications and drug-eluting capabilities may contribute to increased manufacturing costs. Accessibility and affordability are crucial factors in determining how widely these technologies are adopted. It is important to remember that surface-modified nanostents are a developing field and that since my last update, there may have been new advancements. Always refer to the latest scientific literature and medical sources for the most up-to-date information on this topic.

TARGETED DRUG DELIVERY NANOSTENTS

Nanostents can be made to specifically target tissues or cells. By concentrating therapeutic agents exactly where they are needed, this targeted drug delivery strategy seeks to minimize side effects and increase effectiveness. Targeted drug delivery nanostents involve the use of nanotechnology to precisely deliver therapeutic agents to specific locations within the body. This approach aims to enhance the effectiveness of drug therapy while minimizing side effects [139] (Figure 8).

Nanotechnology allows for the design of stents that can deliver therapeutic agents directly to the site of implantation or other specific locations within the body [140]. Targeted drug delivery aims to minimize the systemic exposure of drugs, reducing the risk of side effects in healthy tissues. This is achieved by concentrating the therapeutic agents on the intended target, such as the stent site in a blood vessel [141]. Nanomaterials enable the engineering of drug release kinetics. This maximizes the effectiveness of therapeutic agents by enabling a gradual, controlled release over time [142]. Drug formulations can be customized thanks to the application of nanotechnology. Different drugs or combinations of drugs can be incorporated into the stent design based on the specific needs of the patient or the condition being treated [143]. Targeted drug delivery nanostents contribute to the concept

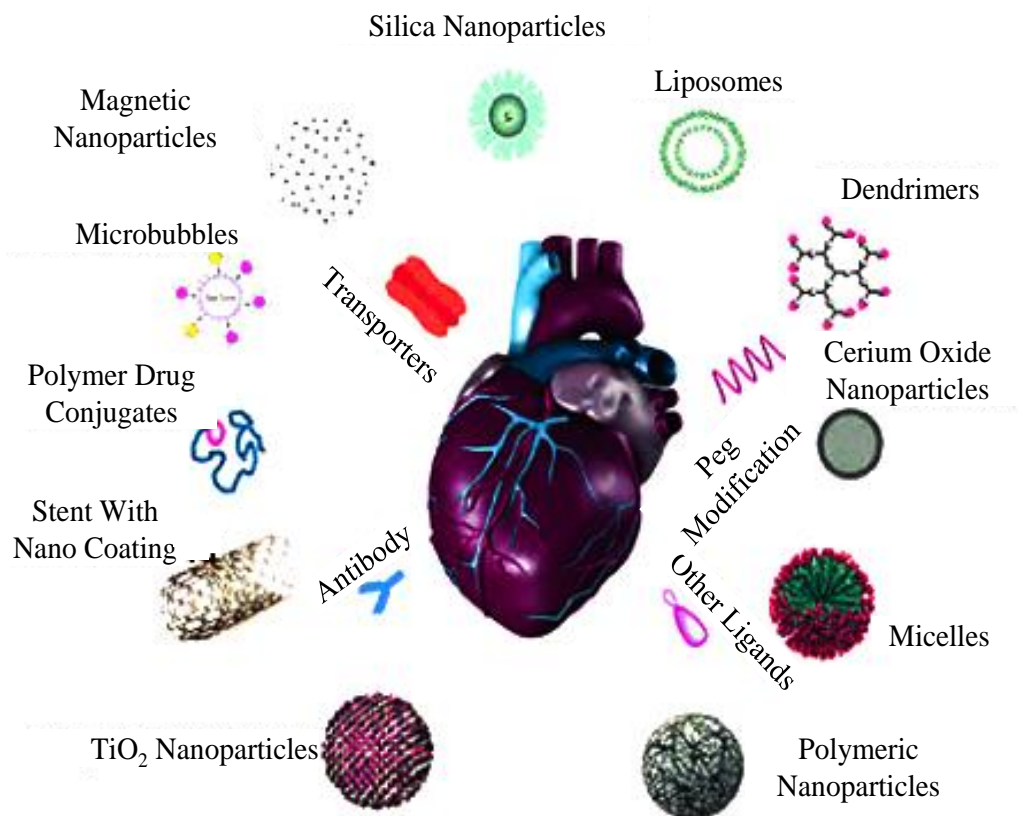


Figure 8. Targeted drug delivery nanostents.

of personalized medicine by tailoring treatment approaches to individual patient characteristics and medical conditions [144]. Nanoparticles can serve as carriers for various therapeutic agents, allowing for a multifunctional approach. This may include combining anti-inflammatory drugs, anti-proliferative agents, or other medications in a single delivery system [145]. Some targeted drug delivery nanostents may have theragnostic capabilities, combining therapeutic and diagnostic functions. For example, they may include imaging agents for monitoring treatment response [146]. By concentrating therapeutic agents at the target site, targeted drug delivery nanostents aim to reduce the impact on healthy tissues, minimizing systemic side effects commonly associated with traditional drug administration [147]. The precise delivery of therapeutic agents to the site of action enhances treatment outcomes by providing a higher concentration of drugs where they are needed most. Research and development in targeted drug delivery nanostents hold great potential for advancing the field of interventional medicine. However, thorough testing, including preclinical studies and clinical trials, is essential to ensure the safety and efficacy of these innovative devices before widespread clinical use [148].

Personalized medication administration in the field of interventional cardiology, nanostents remains a promising area for research and development. By delivering therapeutic agents directly to the affected area, these stents hope to increase the effectiveness of treatment while minimizing side effects on healthy tissues (Table 5).

DIAGNOSTIC NANOSTENTS

Nanotechnology may be employed to enhance the diagnostic capabilities of stents. For example, incorporating nanomaterials with imaging properties could improve visualization during medical imaging procedures. It is important to note that the development of nanostents is an active area of research, and specific types may emerge over time as researchers make advancements in nanotechnology and its application to medical devices [149] (Figure 9).

Table 5. Recent trends, advancements, and drawbacks of surface-modified nanostents.

S.N.	Content	Recent trends and advancements	Drawbacks and challenges
1	Precision Drug Delivery	Targeted drug delivery nanostents leverage nanotechnology to precisely deliver therapeutic agents to specific locations within blood vessels. This precision allows for a localized treatment approach, minimizing systemic exposure.	It is essential to make sure that the drug delivery components and stent materials are biocompatible. The efficaciousness and safety of the stent may be compromised by immune reactions or unfavorable responses.
2	Customized Treatment	Advancements in manufacturing techniques enable the customization of targeted drug delivery stents based on individual patient characteristics. Adapting the course of treatment to each patient's unique requirements can improve the therapeutic outcome.	The mechanical properties of the stent, including its flexibility and radial strength, must be carefully balanced to provide adequate support to the blood vessel while facilitating drug delivery.
3	Combination Therapies	Researchers are exploring the integration of multiple therapeutic agents within the nanostent to address various aspects of vascular healing. This may include anti-inflammatory drugs, anti-proliferative agents, and other compounds to optimize treatment effects.	Maintaining the stability of the drug within the stent over the desired treatment period is a challenge. Factors such as drug degradation and stent wear may impact the long-term stability of the treatment.
4	Real-time Monitoring	Some targeted drug delivery nanostents incorporate technologies for real-time monitoring of drug release and tissue response. This allows clinicians to adjust treatment strategies based on the patient's evolving condition.	The unique features of targeted drug delivery nanostents may pose challenges in obtaining regulatory approval. Comprehensive studies demonstrating safety and efficacy are essential for regulatory clearance.
5	Bioresponsive Coatings	Some targeted drug delivery nanostents incorporate technologies for real-time monitoring of drug release and tissue response. This allows clinicians to adjust treatment strategies based on the patient's evolving condition.	Customization and the use of cutting-edge technologies could drive up production costs. Accessibility and cost-effectiveness are crucial factors for broad adoption, particularly in environments with limited resources. It is crucial to remember that the field of targeted drug delivery nanostents is ever-evolving, and since my last update, new or existing challenges may have been addressed by ongoing research. For the most up-to-date information on this subject, always refer to the most recent publications in science and medicine.

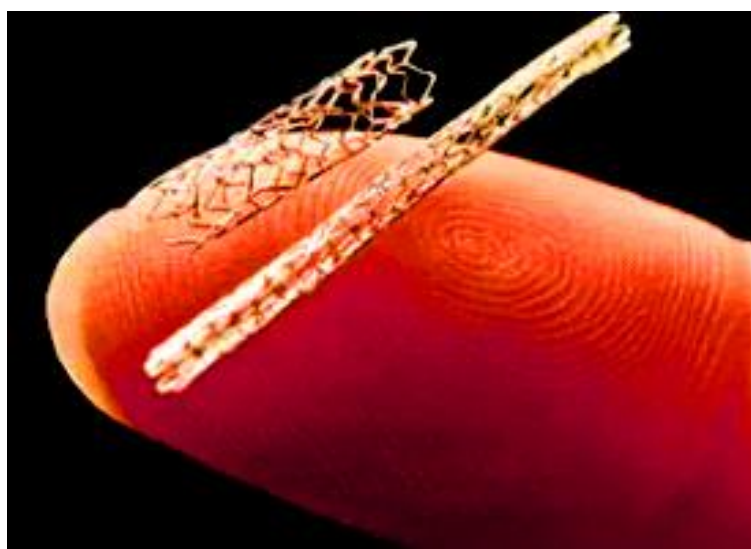


Figure 9. Enhance the diagnostic capabilities of stents.

The statement succinctly captures the essence of how nanotechnology can be harnessed to enhance the diagnostic capabilities of stents. By incorporating nanomaterials with imaging properties, such as nanoparticles that respond to imaging modalities like MRI or ultrasound, researchers aim to improve the visualization of blood vessels and surrounding tissues during medical imaging procedures.

Diagnostic nanostents have been an area of evolving research and development within the medical field. Diagnostic nanostents are designed to not only provide structural support to blood vessels but also incorporate diagnostic capabilities, enabling real-time monitoring and assessment of vascular conditions (Table 6).

Table 6. Recent trends, advancements, and drawbacks of diagnostic nanostents.

S.N.	Content	Recent trends and advancements	Drawbacks and challenges
1	Integrated sensors	Diagnostic nanostents often include integrated sensors or imaging components at the nanoscale. These sensors may utilize technologies such as nanoscale imaging, spectroscopy, or other modalities to provide detailed information about the vascular environment.	Ensuring that the diagnostic components are biocompatible and do not elicit an adverse tissue response is crucial. The interaction between the diagnostic nanostent and surrounding tissues should be carefully studied to avoid complications.
2	Real-time monitoring	Advanced diagnostic nanostents enable real-time monitoring of physiological parameters, such as blood flow, pressure, or changes in vessel diameter. This capability allows for continuous assessment of the stent's performance and the patient's condition.	Miniaturizing diagnostic components to the nanoscale poses engineering challenges. Achieving the necessary sensitivity and accuracy in diagnostics while maintaining a small size is a complex task.
3	Multimodal imaging	Some diagnostic nanostents incorporate multimodal imaging technologies, combining different imaging modalities for a comprehensive assessment of the vascular structure and any potential issues, such as plaque buildup or stent deployment problems.	Some diagnostic features may require power sources for continuous monitoring. Incorporating a reliable and biocompatible power supply within the nanostent presents challenges, especially considering the limited space available.
4	Wireless communication	Integration of wireless communication capabilities enables the transmission of diagnostic data from the stent to external monitoring devices. This can facilitate remote monitoring and timely intervention based on the received information.	Transmitting diagnostic data wirelessly raises concerns about data security and patient privacy. Ensuring secure communication and protecting patient information are critical considerations.
5	Biosensors for biomarkers	Diagnostic nanostents may include biosensors capable of detecting specific biomarkers associated with vascular diseases or inflammation. This allows for early detection and personalized treatment strategies.	Diagnostic nanostents with novel features may face regulatory challenges due to the need for thorough validation of their safety and efficacy. Meeting regulatory requirements for approval is a crucial step in bringing these devices to clinical use. It is important to note that the field of diagnostic nanostents is dynamic, and ongoing research may have addressed or identified new challenges since my last update. Always consult the latest scientific literature and medical sources for the most current information on this topic.

The use of nanotechnology in stents aligns with the broader trend of employing nanomaterials for targeted drug delivery, imaging, and diagnostics in the field of medicine. The precise engineering of materials' properties to meet medical needs is made possible by the ability to manipulate materials at the nanoscale. As research progresses, different types of nanostents with various functionalities and applications will likely emerge. These innovations hold the potential to improve both the diagnostic and therapeutic aspects of cardiovascular interventions. Keeping an eye on scientific literature and developments in the field will provide insights into the specific types of nanostents and their potential impact on medical practice.

CONCLUSION

In conclusion, the research on nanostents has provided valuable insights into the development of advanced medical devices for cardiovascular applications. The investigation encompassed a comprehensive range of methodologies, from material selection and fabrication techniques to *in vitro* and *in vivo* assessments. The selection of nanomaterials for constructing the stent demonstrated promising results in terms of biocompatibility and mechanical properties. The chosen fabrication techniques proved effective in creating nanostents with the desired structural and functional attributes. *In vitro* studies confirmed the cytocompatibility of the nanostent, indicating a favorable interaction with biological environments. Additionally, *in vivo* studies demonstrated. Nanostents designed with drug delivery capabilities exhibited controlled and sustained release of therapeutic agents, as evidenced by mechanical testing revealing the nanostent's ability to withstand physiological conditions, ensuring adequate strength, flexibility, and radial support. Medical imaging techniques provided clear visualization of the nanostent deployment, offering insights into its positioning and interaction with the vascular system. The long-term durability studies indicated. The positive outcomes of this research suggest that nanostents hold significant promise for clinical applications. Their biocompatibility, controlled drug release, and mechanical robustness position them as potential candidates for improved treatments in cardiovascular interventions. While the findings are promising, further research is warranted to address and explore additional aspects such as potential areas for improvement or optimization. Future studies may also focus on scalability and clinical trials to assess the real-world efficacy and safety of nanostents. In instantaneous, the comprehensive investigation into nanostents has provided a foundation for advancing cardiovascular interventions. The positive outcomes observed in this study pave the way for continued research and development, with the ultimate goal of translating these innovations into improved patient outcomes in clinical settings.

Funding

The authors received no financial support for the research, authorship, and publication of this article.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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