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Strategies to Mitigate Biliary Stent Migration Post-Coronary Angioplasty

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ABSTRACT

Implantation of cardiovascular stents has surfaced as a forefront to treat coronary artery diseases through Percutaneous Coronary Intervention (PCI). However, stent migration is a significant complication that arises in a subset of patients, potentially leading to fatal outcomes. Current strategies including self-expanding stents, drug-eluting coatings, and imaging-guided placement are evaluated alongside emerging innovations like high-density lipoprotein (HDL)-infused coatings, 3D printing, and biodegradable stent materials. This review examines underlying mechanisms of stent migration, focusing on patient-specific, procedural, and design-related factors. By addressing stent migration, this research aims to enhance patient outcomes and advance the efficacy of PCI interventions.

Background and Context

Overview of Percutaneous Coronary Intervention and Stenting

Percutaneous coronary intervention (PCI) is a widely used procedure for the treatment of coronary artery disease, offering a minimally invasive approach to restore blood flow in occluded coronary arteries. PCI involves clearing the blockage and deploying a stent to maintain vessel patency.

Stents, small mesh-like devices, act as scaffolds to prevent arterial collapse and reduce the risk of restenosis, or the recurrence of artery narrowing after PCI or angioplasty. Over time, stent technology has evolved from bare-metal stents (BMS) to drug-eluting stents (DES), which release medications to inhibit tissue regrowth, and bioresorbable stents, designed to dissolve after fulfilling their structural role [1][2].

Coronary Stents: Applications and Challenges

Coronary stents are critical components of percutaneous coronary intervention (PCI), a procedure designed to restore blood flow in narrowed or blocked coronary arteries caused by atherosclerosis. Blockages form when fatty deposits, or plaques, accumulate on the arterial walls, a condition that restricts blood flow and can lead to chest pain (angina) or myocardial infarction (heart attack) [3]. During PCI, these blockages are addressed through balloon angioplasty, a process in which a catheter equipped with a small balloon is inserted into the coronary artery. Once the balloon is inflated, the plaque is compressed against the arterial walls, creating a clear pathway for blood flow [1][3].

After angioplasty, stents are deployed to ensure the artery remains open and to prevent restenosis—re-narrowing caused by tissue regrowth or elastic recoil. These stents, small mesh-like tubular devices, are expanded at the site of the blockage using either a balloon or self-expanding mechanisms. The stent serves as a scaffold, supporting the artery while it heals. Depending on the patient's needs, clinicians may use bare-metal stents (BMS), drug-eluting stents (DES) that release medication to inhibit tissue growth, or bioresorbable stents that dissolve over time, eliminating long-term risks associated with permanent implants [2][3].

While stents have greatly improved the outcomes of PCI, complications can still arise. A particularly notable complication is stent migration, where the stent dislodges from its deployment site. Migration can result from inadequate anchoring, challenging vessel anatomy, or material-related issues such as ultrathin designs that lack sufficient radial force. This complication poses significant risks, including arterial occlusion, embolization, and thrombosis, often necessitating additional interventions to retrieve or reposition the stent [1][3]. Efforts to address stent migration focus on refining stent designs, optimizing deployment techniques, and leveraging advanced imaging technologies to enhance procedural accuracy and patient safety.

Understanding Stent Migration

Stent migration, although rare, poses significant clinical challenges in both cardiovascular and non-cardiovascular interventions.

Cardiovascular Stenting

In the context of percutaneous coronary intervention (PCI) performed for cardiovascular diseases, studies report the incidence of stent migration to range from 0.9% to 8.4%, depending on procedural and patient-specific factors [4]. Migration often occurs due to inadequate anchoring of the stent, improper sizing, or dislodgment caused by high-pressure blood flow in coronary arteries. Ultralow-profile or ultrathin stents, while offering flexibility and reduced restenosis risk, are more susceptible to dislodgment due to their reduced structural integrity [6].

The consequences of stent migration in cardiovascular applications can be severe, including arterial occlusion, embolization, or even death. For instance, a recent case report described a coronary stent deployed in the left anterior descending artery that migrated to the infrarenal aorta. The stent was retrieved during an aortobifemoral bypass procedure, and the patient experienced no postoperative complications, with follow-up imaging showing no recurrent stenosis [6]. Such rare occurrences underscore the critical importance of accurate deployment techniques and the need for stents designed to mitigate migration risks in coronary arteries.

Non-Cardiovascular Stenting (Biliary Interventions)

In biliary stenting performed for non-cardiovascular conditions, such as bile duct obstructions caused by malignancies or gallstones, migration rates are comparatively higher. Research indicates that the migration rates for plastic biliary stents range from 5% to 10%, with distal migration occurring in 3% to 6% of cases [5]. Contributing factors include anatomical challenges like wide or dilated bile ducts, benign biliary strictures, or prior procedures such as sphincterotomy. The use of straight or inadequately sized stents increases the risk of migration, whereas designs with enhanced anchoring, such as double pigtail stents, reduce this risk [5].

While biliary and coronary stenting address different anatomical and clinical challenges, the common underlying issues—improper anchoring, sizing errors, and structural limitations—demonstrate the shared need for innovative solutions.

Broader Implications

Understanding the distinct risks of stent migration in cardiovascular and noncardiovascular contexts highlights the need for continuous innovation in stent design, procedural protocols, and patient-specific approaches. Efforts to address migration risks include developing stents with enhanced anchoring mechanisms, refining deployment techniques with advanced imaging, and tailoring interventions to the unique anatomical and physiological characteristics of each patient population.

Mechanisms of Stent Migration

Patient-Specific Factors

Certain patient-related anatomical and physiological characteristics can predispose individuals to stent migration. Anatomical variations, such as tortuous or highly calcified coronary arteries, increase the difficulty of proper stent anchoring and elevate the risk of dislodgment. Comorbid conditions, such as peripheral arterial disease, may exacerbate migration risks by altering vascular dynamics and creating areas of high turbulence or flow resistance [4][6]. Additionally, high blood flow pressures in large vessels, such as the aorta, can force stents to move, as demonstrated in the case of Kerr et al. (2024), where a coronary stent migrated into the infrarenal aorta during a period of prolonged vascular stress [6].

Procedure-Related Factors

Errors during stent placement or procedural complexities significantly contribute to migration risk. Suboptimal deployment, including inadequate stent expansion or poor apposition to the vessel wall, may result in incomplete anchoring. The use of improper stent sizing—too small or too large for the target artery—further increases the likelihood of dislodgment [4]. In procedures involving overlapping stents, particularly in high-flow areas, insufficient overlap or misalignment can lead to migration, as overlapping stents rely on precise positioning for stability. Additionally, emergency or high-risk PCIs performed under time constraints may elevate procedural errors, inadvertently increasing the chance of stent migration [4][6].

Design and Material Limitations

The structural design and material composition of a stent are critical factors influencing migration risk. Ultralow-profile or ultrathin stents, while advantageous for minimizing restenosis and enabling flexibility, are more prone to dislodgment due to their reduced structural integrity [6]. Stents made from materials with lower radial strength may fail to maintain sufficient pressure against the arterial walls, particularly in regions of high turbulence. Conversely, overly rigid stents may be unable to conform to curved or irregular arterial anatomies, leading to poor adherence and eventual displacement. Emerging materials, such as biodegradable polymers, offer potential advantages but require further testing to assess their stability and resistance to migration [3][6].

Current Strategies to Prevent Stent Migration

Improved Stent Designs

Advancements in stent design have significantly reduced the risk of migration by improving anchoring capabilities and adaptability. Self-expanding stents, for example, provide greater radial force and flexibility, allowing them to conform better to irregular or tortuous arterial anatomies. Designs incorporating anti-migration features, such as barbs or flanges, enhance anchoring stability, particularly in high-flow regions [4]. Additionally, hybrid designs that combine flexible and rigid elements improve compatibility with complex vessel geometries while maintaining resistance to displacement. Innovations in biodegradable stents have further improved stent functionality, as these materials integrate seamlessly with the vessel wall before gradually dissolving, eliminating long-term risks of migration [3].

Drug-Eluting and Bioactive Coatings

Drug-eluting stents (DES) release antiproliferative agents, such as sirolimus or paclitaxel, that inhibit neointimal hyperplasia, reducing the risk of restenosis—a contributing factor to stent migration [2]. Beyond drug-eluting coatings, bioactive stents with surface modifications promote endothelialization, enhancing the integration of the stent with surrounding tissues. Emerging bioactive materials, including high-density lipoprotein (HDL) coatings, have shown promise in improving stent biocompatibility and reducing the risk of thrombosis and migration [2]. These innovations aim to create a smoother interface between the stent and arterial wall, minimizing dislodgement risks.

Customized Stenting Using Imaging Technologies

The integration of advanced imaging technologies into stent placement procedures has transformed the precision of stent deployment. High-resolution modalities, such as intravascular ultrasound (IVUS) and optical coherence tomography (OCT), enable real-time visualization of vessel anatomy, allowing for accurate stent sizing and optimal positioning [4]. In addition, 3D printing technologies have emerged as a revolutionary tool for creating patient-specific stents tailored to unique anatomical features [1][3]. These customized stents conform perfectly to the vessel walls, reducing the likelihood of migration and enhancing overall procedural outcomes.

Innovative Approaches and Emerging Solutions

High-Density Lipoprotein (HDL) Therapy

High-density lipoprotein (HDL) therapy has emerged as a promising approach to enhance stent biocompatibility and reduce migration risks. HDL coatings on stent surfaces promote rapid endothelialization, integrating the stent with the arterial wall and reducing the risk of dislodgment. These coatings also exhibit anti-inflammatory and antithrombotic properties, addressing key factors that contribute to complications like restenosis and thrombosis [2]. Preliminary studies indicate that HDL-infused stents demonstrate improved vascular healing compared to traditional drug-eluting stents, offering a dual advantage of biological integration and structural stability. This innovative approach has the potential to revolutionize stent design, particularly in high-risk patients.

3D Printing for Personalized Stents

The advent of 3D printing technology has introduced the possibility of creating personalized stents tailored to individual patient anatomies. By leveraging high-resolution imaging data, such as intravascular ultrasound (IVUS) or computed tomography angiography (CTA), 3D-printed stents can be customized to fit the unique dimensions and curvature of a patient's coronary arteries [1][3]. These personalized stents improve wall apposition and reduce the risk of migration by providing an exact fit, even in tortuous or irregular vessels. Additionally, the versatility of 3D printing allows for the integration of novel designs and materials, including biodegradable or hybrid components, to further enhance stent functionality and patient outcomes.

Biodegradable and Hybrid Material Stents

Biodegradable stents, constructed from materials such as magnesium alloys or polymer-based compounds, are designed to dissolve gradually after fulfilling their mechanical role. This feature eliminates long-term risks associated with permanent implants, such as late thrombosis or chronic inflammation. Biodegradable stents offer the added advantage of reducing the likelihood of migration, as their gradual absorption integrates them with the surrounding tissue over time [3]. Hybrid material stents, which combine rigid and flexible elements, have also shown promise. These stents provide the structural strength required for high-flow arteries while maintaining sufficient flexibility to adapt to complex anatomies, minimizing migration risks in both straightforward and challenging cases [3].

Challenges in Implementation

Cost and Scalability

Innovative stent technologies, such as biodegradable materials, HDL-infused coatings, and 3D-printed stents, come with significant cost implications. Biodegradable stents, while promising for reducing long-term complications, require advanced manufacturing processes that are more expensive than those for traditional metal stents [3]. Similarly, 3D-printed stents demand high-resolution imaging, specialized equipment, and expertise, making them less accessible for widespread clinical use [1][3]. The scalability of these technologies remains a challenge, as high production costs and limited resources in developing healthcare systems can restrict their availability to a broader patient population.

Regulatory and Ethical Considerations

The introduction of new stent technologies requires rigorous testing and regulatory approval to ensure safety and efficacy. Biodegradable and hybrid stents must demonstrate equivalent or superior performance to existing devices through extensive preclinical and clinical trials, which can delay their entry into the market [3]. Ethical considerations also arise in ensuring equitable access to these innovations, as high costs and limited availability could exacerbate disparities in healthcare access. Additionally, the personalized nature of 3D-printed stents raises questions about the standardization of care and the long-term reliability of custom devices [1][3].

Clinical Integration and Training

The adoption of advanced stent technologies demands comprehensive training for interventional cardiologists and related healthcare providers. Techniques for deploying biodegradable stents or using imaging-guided placement tools, such as intravascular ultrasound (IVUS) or optical coherence tomography (OCT), require specialized knowledge and experience [4]. Moreover, integrating 3D printing into clinical practice involves a steep learning curve, as it requires expertise in imaging interpretation, design customization, and deployment of personalized devices. Addressing these training gaps is essential for ensuring the successful implementation of innovative solutions and improving patient outcomes [3][4].

Discussion

Comparative Analysis of Techniques

Current strategies for preventing stent migration, including improved stent designs, drug-eluting coatings, and advanced imaging technologies, each have unique strengths and limitations. Self-expanding stents offer superior adaptability in tortuous vessels but may still face challenges in anchoring under high-pressure blood flow [4]. Drug-eluting stents (DES) significantly reduce the risk of restenosis through antiproliferative agents, yet they rely on proper deployment and sizing to minimize migration risks [2]. Advanced imaging modalities like intravascular ultrasound (IVUS) and optical coherence tomography (OCT) enhance precision during deployment, improving stent apposition and placement accuracy, but their reliance on costly equipment limits widespread use [4].

Emerging solutions, such as biodegradable stents and HDL-infused coatings, present promising alternatives. Biodegradable stents eliminate long-term risks associated with permanent implants, yet concerns about their mechanical strength and degradation rates persist [3]. Similarly, HDL-coated stents show potential in promoting vascular healing and integration, but more clinical trials are needed to validate their efficacy and long-term safety [2]. Personalized stents produced via 3D printing may revolutionize patient-specific interventions, but their scalability and cost remain significant hurdles [1][3].

Future Directions for Research and Development

The future of stent technology lies in integrating precision medicine, advanced materials, and real-time imaging. Research into hybrid stents that combine biodegradable and permanent elements could address current limitations, offering both short-term support and long-term integration [3]. Developing stents with dynamic anchoring mechanisms—capable of adapting to changes in vessel geometry and blood flow—could significantly reduce migration risks. Further studies are needed to optimize the performance of ultrathin and ultralow-profile stents while maintaining structural integrity.

Expanding the use of HDL coatings in stent design could bridge the gap between biological integration and mechanical stability, addressing both restenosis and migration risks [2]. Future research should also focus on refining 3D printing techniques to produce stents that are not only customized but also cost-effective and scalable for broader clinical application [1][3]. Lastly, incorporating artificial intelligence (AI) and machine learning into imaging technologies could enhance real-time analysis during deployment, improving precision and reducing human error in stent placement [4].

Conclusion

Stent migration remains a challenging complication in percutaneous coronary intervention (PCI), posing significant risks to patient safety and long-term outcomes. While current strategies, such as improved stent designs, drug-eluting coatings, and advanced imaging technologies, have reduced the incidence of migration, limitations persist. Emerging innovations, including biodegradable stents, HDL-infused coatings, and personalized 3D-printed stents, hold great promise for addressing these challenges by enhancing stent integration, stability, and patient-specific adaptability.

The integration of precision imaging, advanced materials, and customized designs into clinical practice represents a pivotal step forward. However, successful implementation requires addressing significant barriers, including cost, scalability, and the need for specialized training. Ongoing research and interdisciplinary collaboration are essential to overcoming these obstacles and ensuring that innovative solutions are both accessible and effective.

By continuing to refine stent technologies and procedural techniques, the field of interventional cardiology can advance toward minimizing complications like migration, ultimately improving outcomes for patients undergoing PCI. As these innovations are validated through clinical trials and translated into widespread practice, they will pave the way for safer, more effective interventions that address the complexities of coronary artery disease.

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