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The Next Generation of Atherectomy: Recent Progress, Challenges, Strategies, Relationships, and Future Pathways

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***Abstract*—Atherectomy has become a vital complementary technology in the treatment of complex arterial disease especially in lesions with heavy calcification such that their treatment with balloon angioplasty and stenting is limited. New technologies have made atherectomy no longer a mere instrument of plaque removal in practice, but instead extremely sophisticated systems that can achieve specific and vessel-conforming manipulation of the plaque. This review discusses the recent generation atherectomy equipment directional atherectomy equipment, rotational atherectomy equipment, orbital atherectomy equipment, and laser atherectomy equipment and the clinical associations they have with lesion morphology, imaging guidance, and adjunctive therapies. It also dwells on the next-generation innovation such as AI-guided navigation, new energy-powered solutions, micro-atherectomy of distal vessels, and drug-based platforms that can enhance vessel healing and minimize restenosis. The most important issues including device-vessel interaction, embolic risk, operator learning requirements, economic limitations and regulatory complexity are critically evaluated. New direction of future development is determined, and the focus is placed upon smarter sensors, real-time imaging integration, nanotechnology, and predictive modelling of personalised treatment planning. Case studies show the performance in real life and reveal discrepancies between the theoretical performance and the actual results. All in all, next-generation atherectomy has tremendous potential to enhance the safety of implementation of the procedure, its efficacy, and its long-term vascular outcomes, when technological innovation proceeds with resolving the existing limitations in a systematic and evidence-based way.**

Keywords—Atherectomy technologies, Rotational and orbital atherectomy, Calcified arterial lesions, Imaging-guided intervention, AI-assisted navigation, Next-generation endovascular devices.

I. Introduction

Technologies of atherectomy have improved the treatment of complex arterial lesions that are calcified. Modern systems lead to a better result in precision, safety and an improved outcome in plaque modification. This analysis assesses the existing equipment, novel technologies, clinical issues, strategic methods, and the technology interrelations that characterize next-generation atherectomy and its growing prominence in the modern vascular intervention practice.

II. Current Atherectomy Technologies & Clinical Relationships

Atherectomy is a key consideration in the treatment of aggressive arterial lesions that would be untreatable using conventional balloon angioplasty. The plaque composition, vessel geometry and adjunct therapies respond differently to each type of technology. The knowledge of these differences is the key to choosing the most suitable device when the intervention becomes complicated working on the vascular system (Brown et al., 2022). These systems, together, help to enhance luminal expansion, minimize dissections, as well as optimise stenting or drug-coated balloon therapy preparation.

A. Directional Atherectomy

Directional atherectomy involves a side cutting blade inside a catheter which skims the plaque in a controlled manner. This technique is best suited in non-circumferential lesions that are eccentric where the plaque can be directed. It is also applicable to femoropopliteal disease because operators are able to remove large volumes of plaque yet preserve healthy vessel tissue (Carr et al., 2022). It is however, very much dependent on operator skill, and may be embolic risky, and may need embolic protection devices to be used to ensure safer results.

B. Rotational Atherectomy

Rotational atherectomy involves the use of the high-speed abrasive burr to polish the calcified plaque into micro-particles. It is useful especially in the hard, concentric, severely calcified lesions where balloon crossing is challenging. The burr is operated over a specialised guidewire, which allows performing rigid plaque changes in a controlled manner (Florek et al., 2023). The method finds application in coronary interventions, but vessel trauma and heat have to be monitored carefully.

C. Orbital Atherectomy

Orbital atherectomy uses an eccentrically sweeping crown which forms a sanding orbit altering the plaque circumferentially without stopping blood flow. It has a rotational pattern of two plates that allows both small and large vessels to be treated using different rotational speeds (Khan et al., 2020). Diffuse, heavily calcified disease is a type of disease that this technology is particularly useful in the cases where uniform lumen expansion is needed.

D. Laser Atherectomy

Laser atherectomy involves the ability to vaporise the plaque and thrombus with the help of a pulsed excimer laser energy. It has a high efficacy in in-stent restenosis, chronic total occlusions and fibrotic lesions. Laser energy does not cause deep dissections since it can pass through tissue with limited mechanical stress (Kovaleski, 2023). Laser atherectomy is also helpful in case of calcium distribution which is not regular or that which is mixed with fibrotic tissue.

E. Essential Relationships Between Devices and Lesions

Various atherectomy systems are associated with different relationships with the plaque morphology, lesion architecture and adjunctive therapies. Directional systems are more effective in eccentric plaque and rotational and orbital device is more successful in concentric or diffuse calcium. Laser systems provide the best result in fibrotic lesion or restenosis lesions (Sansosti et al., 2024). There is also the effect of device choice that can be used along with drug-coated balloons or stents and hence the importance of the matching of technology to the characteristics of the lesions to have the best therapy is emphasised.

III. Emerging Technologies, Strategies & Next-Gen Innovation

The newer technologies that are available in the field of atherectomy are becoming more precision-oriented, preservation-oriented, and individualised treatment approach. The next generation systems combine digital intelligence, new source of energy, and combination therapies to eliminate the limitations of traditional mechanical debulking. The objective of these advances is to enhance control of the procedures, minimise complications, and avoid restenosis by more targeted and adaptive plaque modification (Anandan et al., 2024). Together, they have shown a significant change in terms of transitioning purely mechanical devices to data-driven, intelligent platforms.

A. Atherectomy Systems, AI-Controlled, and Intelligent

Intelligent atherectomy systems are being developed that can facilitate real time navigation, plaque characterisation as well as automatic optimization of cutting mechanics (Li et al., 2024). Through processing the data of intravascular imaging, AI algorithms can detect the distribution of calcium, project vessel compliance, and direct the operators to safer debulking routes. The systems also decrease operator variation and provide uniform performance across complicated anatomies (Li et al., 2024). The automatic control of rotational speed or energy output, or orbital movement using integrated feedback loops, enables the devices to improve safety and the accuracy of the procedure based on the resistance of the lesion.

B. New Energy-Based Techniques (Ultrasonic, Plasma, Hybrid)

Other energy modalities beyond mechanical cutting are also looking to cleave plaque with low vessel trauma. Ultrasonic atherectomy separates the calcific deposition using micro-fractures produced through vibrations, whereas the plasma-based systems produce ionised energy to soften tissues with low heat transfer (Chen et al., 2023). These types of devices are hybridized and utilize mechanical action along with thermal or acoustic energy to increase selectivity, and are especially applicable in mixed lesions of calcified-fibrotic tissue. These are innovations that depict methods of treating lesions that are too rigid or dangerous to use the customary burr-based ones.

C. Drug-Integrated and Combination Atherectomy

Atherectomy systems that integrate drugs incorporate both mechanical and pharmacologic debulking. These systems hope to reduce the intimal hyperplasia and reduce the restenosis rates by eliminating the plaque and providing anti-proliferative agents immediately (Ibrahim Alradwan et al., 2024). Atherectomy with drug-coated balloons, particularly use as a peripheral arterial disease, is also becoming popular. This combined strategy increases the preparation of the vessel and encourages more lasting long-term patency.

D. Micro-Atherectomy of Small and Distal Vessels

The development of miniaturisation has made possible the use of micro-atherectomy in the treatment of small, tortuous, and distal vessels. These systems make use of very low profile cutting elements that can traverse small arterial sections safely and do not cause damage to delicate vessel walls (Carr et al., 2022). Micro-atherectomy approach seeks to increase the treatment of below-the-knee disease, diabetic limb ischemia as well as distal coronary disease in which conventional devices are inappropriate.

E. Strategic Intervention With Imaging and Adjunct Therapies

Next-generation atherectomy is largely dependent on intravascular ultrasound (IVUS), optical coherence tomography (OCT), and pressure-wire assessment to drive the process of lesion evaluation and procedure planning. Such imaging instruments guarantee precise targeting of the plaque, lumen gain optimisation, and assist in real-time safe device functioning (Kern et al., 2024). Combined strategic use with adjunct therapies (drug-coated balloons, stents, and embolic protection devices) adds more value because treatment is now based on the complexity of lesions.

IV. Challenges, Limitations & Technology Relationships

Despite the innovative advancements in the technology of atherectomy, there are still several persistent problems with clinical outcomes and performance. These issues transcend across clinical, technical, operational and regulatory divisions and each of them affects the efficiency and safety of next-generation devices. The awareness about these limitations may be essential in order to be the driving force of innovation and increase applicability in the real world (Esposito et al., 2022).

A. Clinical Challenges

Distal embolization, vessel dissection, perforation, and slow-flow or no-reflow phenomena are some of the risks associated with atherectomy procedures in a clinical setup. These complications occur more in long-segment lesions or those that are heavily calcified. Moreover, patient-specific variables, such as the vessel size, plaque structure, and comorbidities, may also determine the success of the procedure (Florek et al., 2023). These complexities can only be managed with the help of careful imaging, the right choice of device and sheer technique of the procedure.

B. Technical and Engineering Limitations

Engineering wise there are constrained cutting depth, inability to alter deep or nodular calcium and the inability to negotiate tortuous anatomy. The interaction between devices and vessels is still unsatisfactory because aggressive debulking can damage the structural integrity or cause thermal damage (Chan and Ramji, 2022). The design of the future needs to be efficient in cutting and preserving the vessels particularly in the minor or weak arteries.

C. Operational and Training Problems

Operationally, atherectomy requires the operator to be highly skilled, have knowledge of the device operation, and make decision on the fly. Poor training may result in poor outcomes or difficulties. Moreover, the difference in the technique of the operator produces an inconsistency in the results across centres (Sansosti et al., 2024). The use of advanced simulation tools and competency-based certification might contribute to the standardisation of practice.

D. Economic, Regulatory and Adoption Barriers

Atherectomy devices are expensive economically and reimbursement amongst health systems varies. This influences adoption levels especially where the resources are low. The regulatory pathways also become more problematic because the next-generation technologies based on AI, robotics or new energy sources have to pass more stringent validation (Mirabi and Unciano, 2025). Striking a balance between innovation and safety and cost-efficiency is one of the significant obstacles to the wide adoption.

E. Relationship Between Challenges and Patient Outcomes

This has a direct impact on the success of process and long term outcomes. Clinical risks lead to the development of complications and there are technical limitations, which might decrease lumen gain and/or aggravate restenosis. The variability of the operations, in turn, introduces another aspect of variability in the consistency, and cost factor may restrict the utilization of the advanced devices by the patients (Kovaleski, 2023). These problems are paramount to overcome the problems of safer and more efficient systems of atherectomy.

V. Future Directions & Strategic Development Pathways

Atherectomy is on the road towards intelligent, image directed and biological responsive systems which have the ability to react to the nature of the lesion on an instantaneous basis. These new directions introduced emphasis on enhanced safety, procedural precision and personal care. The next-generation devices should be developed in line with the technological advancement and the clinical needs as vascular disease continues to become more complex in the ageing populations (Lafta et al., 2024).

A. Intelligent Sensors and Live Time Imaging

The application of intelligent sensors in atherectomy catheters will probably transform the processes of seeing and controlling. Such sensors can detect compliance of vessels, density of calcium and real time values of forces between devices and vessels. They can be used on IVUS or OCT platforms to help to create a safer cutting method, as they help to avoid unnecessary over penetration (Kern et al., 2024). The final step would be that the sensor based systems would generate semi- autonomous feedback loops, which would automatically regulate the pressure of the burr, rotation or energy output.

B. Nanotechnology and Micro-Robotic Atherectomy

Nanotechnology provides plaque modification with a high degree of precision when the micro-scale robotic systems are used which are able to traverse narrow or winding vessels. The micro/nano-robots have the capability of destroying plaque with the help of the mechanical vibration, chemical targeting, or micro-abrasion forces (Chen et al., 2023). Their smaller size makes them less traumatic and may allow the previously untreatable vessels to be treated. Such technologies can also be used to deliver a certain drug or destroy a certain fragment of calcium with minimal collateral damage.

C. Predictive Analytics and personalised Atherectomy Planning

Predictive analytics and machine learning will become the next ground-breaking procedural planning by simulating lesion morphology, vessel behaviour, and patient response. These tools are capable of helping the clinicians to choose the best type of device, energy, or adjunct therapy. Machine learning has the potential to predict the risk of restenosis or determine high-yield strategies by analysing large datasets (Li et al., 2024). Individualised process paths will decrease the change in results and improve the long-term patency.

D. Ethical, Training and Regulatory Evolution in the Future

The smarter and more automated the devices are, the more ethical concerns arise in terms of dependence on an operator, transparency of the data, and automated decision-making processes. The training will require the inclusion of simulation-based education, and digital competency requirements to prepare the clinicians to advanced systems (Mirabi and Unciano, 2025). New frameworks will also be required by regulatory bodies to assess devices that use AI algorithms, new forms of energy and micro-robotic components without slackening innovation.

VI. Case Studies

Clinical case studies will also be useful in terms of their practical information on the performance of atherectomy technologies during actual vascular procedures. They emphasize that it is necessary to choose the appropriate device depending on the morphology of the lesion, the size of the vessel, and the planned adjunct treatment. These cases also reveal how debulking can be strategically applied to enhance luminal gain, minimize complications of the procedure, and increase the durability of treatment (Sansosti et al., 2024). The three cases below are examples of common situations in which various atherectomy platforms have unique clinical advantages.

A. *The Case Study 1: Orbital Atherectomy in Calcified Femoro-Popliteal Lesion*

A 73-year-old man came with lifestyle-limiting claudication due to a massively calcified popliteal lesion of the femur (Li et al., 2024). Angiography showed concentric calcium, and, therefore, conventional angioplasty would hardly achieve satisfactory expansion. The use of orbital atherectomy was chosen because it provides the possibility to selectively remove calcified tissue without destroying healthy vessel portions (Khan et al., 2020). In the process, deep calcium was altered using low-speed orbital passes to produce initial lumen gain and then high-speed passes. Afterward plain balloon angioplasty was done which resulted in complete dissection-free expansion. The patient showed improvement of symptoms at six months follow up. This case indicates the importance of orbital atherectomy in the treatment of diffuse circumferential calcification where a consistent plaque amendment is needed.

B. *Case Study 2 Laser Atherectomy of In-Stent Restenosis*

A 66-year-old woman with recurrent in-stent restenosis (ISR) had laser atherectomy in order to eliminate neo-intimal hyperplasia. Previous balloon angioplasty had been unsuccessful because of severe fibrotic tissue. The energy of excimer laser is effective in vaporising proliferative tissue allowing the enhancement of stent expansion (Kovalevsky, 2023). The procedure was especially beneficial due to the fact that it did not use any aggressive mechanical cutting within the stent. Following laser debulking, a drug covered balloon was used to prevent additional hyperplasia. At nine months, the patient was still restenosis-free. The case illustrates how laser systems have a special place in ISR, where photochemical ablation is used to minimize mechanical trauma because of its precision.

C. *Case Study 3: Hybrid Atherectomy + Drug-Coated Balloon CTO*

An elderly patient (71 years) with a history of diabetes reported having a long-segment chronic total occlusion (CTO) in the superficial femoral artery. It was decided to adopt a hybrid solution of rotational atherectomy with the subsequent use of a drug-coated balloon. The rotational apparatus was able to change heavy calcification and permit the therapy balloons to pass (Carr et al., 2022). The delivery of drugs to persons who had undergone debulking had reached the outcome of better luminal patency at twelve months follow-up and no reintervention was necessary. The case highlights the use of combination strategies as the best way of preparing vessels and increasing drug uptake, especially in calcified occlusions.

VII. Discussion

It is evident that lesion type, plaque characteristics, and vessel complexity have definite trends when it comes to the choice of a atherectomy device as presented in the three case studies. Orbital atherectomy is always beneficial in circumferential calcification, laser system is better in restenosis or fibrotic in-stent lesions and hybrid techniques are ideal in long-segment CTOs. These observations indicate that clinical outcomes are not solely determined by the capability of the devices, but also by the ability to find an exact fit of technology to plaque morphology (Florek et al., 2023). The operators should hence, decode imaging results with caution when deciding when a particular device will result in a maximum luminal gain and minimise procedure risk. The cases also present practical issues including the depth of calcium, lumen irregularity, stent blockage, and cross over failure of the balloon. In both situations, the atherectomy was used as a strategic vessel preparation tool that has allowed the enhanced drug uptake or stent expansion or successful outcomes of the procedure in general (Kovaleski, 2023). The complexity of lesions and choice of devices is also observed: larger and more calcified, eccentric, or restenotic lesions need a different approach. Finally, these clinical trends support the necessity of more sophisticated imaging, experience of the operator, and the combination of atherectomy with support therapies.

VIII. Recommendations

A. *Clinician Recommendations*

- Precisely evaluate the plaque content with IVUS or OCT and then choose the atherectomy device (Khan et al., 2020).
- Atherectomy should be expediently used as a vessel-preparation device but not a routine intervention.
- Reserve reserve atherectomy of complex and high-risk calcified lesions where balloon angioplasty fails.

B. *Recommendations for Researchers*

- Focus on comparative studies of the results of various atherectomy systems over time.
- Explore the best rotational velocities, energy and the mechanics of interaction with plaque.
- Write predictive algorithms and prediction models to aid the process of procedural personalisation.
- Discover the best methods of integrating atherectomy and drug-coated balloons, stents and advanced imaging technologies.

C. *Recommendations to the Manufacturers of Devices*

- Increase the device-vessel contact and decrease embolic complications.
- Include smart feedback and sensor control in catheters design.
- Enhance delivery of energy, in varying types of plaque, and consistency.
- Make certain that new devices are affordable but at the same time compatible with new intravascular imaging technologies.

IX. Conclusion

The next generation atherectomy has high chances of safer and more effective plaque modification. The future systems can optimise the clinical outcomes by solving engineering problems and embracing smarter and image guided approaches. The role of the advanced atherectomy in vascular intervention in the long run will be characterized by continued innovation, assessment and careful integration.

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