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Applications and Future Perspectives of Intravascular Ultrasound in Endovascular Treatment of Lower Extremity Arteries

Xinyi Li, Yuchi Zou, Xiangyu Liu, Jun Cheng*

The First Affiliated Hospital of Chongqing Medical University, Chongqing 400016, China
**Correspondence Author*

Abstract: ***Intravascular ultrasound (IVUS) is a high-resolution imaging modality that plays a critical role in the endovascular treatment of lower extremity arterial disease. This review summarizes the principles, device types, and technical characteristics of IVUS, with a focus on its applications in lesion assessment, guidewire navigation, real-time monitoring, and follow-up. Research has demonstrated that IVUS significantly enhances treatment success rates by providing detailed imaging of vascular structures and aiding precise intervention planning. However, its widespread adoption is limited by operational complexity and high costs. Emerging technologies, including all-optical IVUS, artificial intelligence, and big data analytics, promise to address these challenges and expand IVUS applications. These advancements are expected to further improve diagnostic accuracy and therapeutic outcomes, highlighting the promising future of IVUS in managing lower extremity arterial disease.***

Keywords: Intravascular ultrasound, Lower extremity arterial disease, Endovascular therapy, Imaging technology.

1. Introduction

Peripheral artery disease (PAD) is a chronic vascular condition primarily caused by atherosclerosis, leading to restricted blood flow in the lower extremities [1]. Severe cases can result in tissue necrosis or amputation [2]. PAD is highly prevalent, particularly among the elderly, and is closely associated with risk factors such as smoking and diabetes [2]. Imaging techniques play a vital role in its diagnosis and treatment, with intravascular ultrasound (IVUS) emerging as a key tool [3]. IVUS, as a high-resolution imaging modality, captures detailed images of vascular structures, aiding in lesion assessment, guidewire navigation, stent optimization, and post-treatment monitoring [4]. Despite challenges such as operational complexity and costs, the integration of IVUS with artificial intelligence (AI) and all-optical systems holds the potential to revolutionize PAD management, enhancing clinical precision and patient outcomes [5]. This review critically evaluates IVUS principles, applications, and future directions in the endovascular treatment of lower extremity arterial diseases.

2. Literature Search and Methods

This review is based on an analysis of peer-reviewed studies published between 2000 and 2023, sourced from PubMed, Scopus, and MEDLINE databases. Keywords such as "intravascular ultrasound (IVUS)," "peripheral artery disease," "endovascular therapy," "imaging technology," and "artificial intelligence" were utilized. Inclusion criteria focused on studies that evaluated IVUS in PAD treatment, compared IVUS with other imaging modalities, or explored its efficacy in guiding interventions and improving outcomes.

3. Applications of IVUS in Lower Extremity Endovascular Therapy

3.1 Qualitative Measurements

3.1.1 Lesion and Plaque Characterization

IVUS provides detailed information about lesion types and plaque characteristics, essential for treatment planning [6, 7]. Plaques can be categorized based on echogenicity:

Fibrous Plaques: Appear as homogenous high-reflection areas [8]. (Figure 1 E)

Lipid-Rich(soft) Plaques: Exhibit low echogenicity and are associated with instability [9]. (Figure 1 F)

Calcified Plaques: Present as high-echogenicity regions with acoustic shadows [10]. (Figure 6 C)

Mixed Plaques: Comprise varying components, appearing heterogeneous on IVUS [11]. (Figure 1 D)

Thrombus: Identified as irregular masses protruding into the lumen [12]. (Figure 1 B,C)

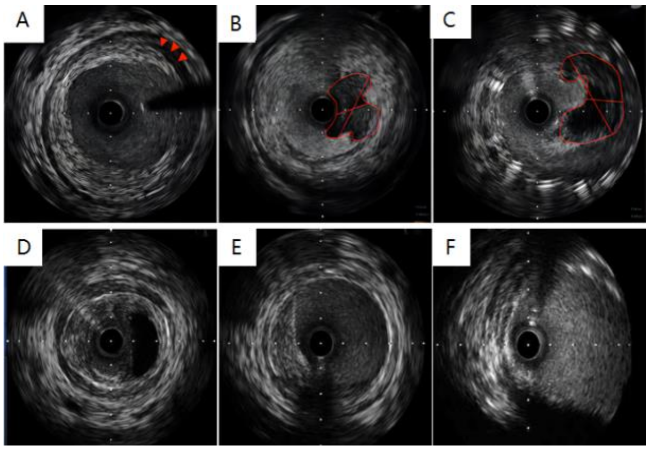

Figure 1: Plaque and Lesion Types
Notes: A. The arrow indicates a mobile intimal flap; B. Highlighted area shows intraluminal mural thrombus in restenosis; C. Highlighted area shows complete in-stent occlusion with thrombus formation; D. Mixed plaque; E. Fibrous plaque; F. Soft plaque.

3.1.2 Vessel Wall Assessment

IVUS visualizes the three-layered arterial wall: intima, media, and adventitia [13]. The intima includes the internal elastic membrane (IEM), visible as a bright echo band. The external elastic membrane (EEM) at the media-adventitia boundary often appears irregular in atherosclerotic vessels, reflecting vascular remodeling [7]. IVUS is also valuable for detecting arterial dissections (Figure 3) and calcifications (Figure 4), helping to refine treatment strategies [14][8].

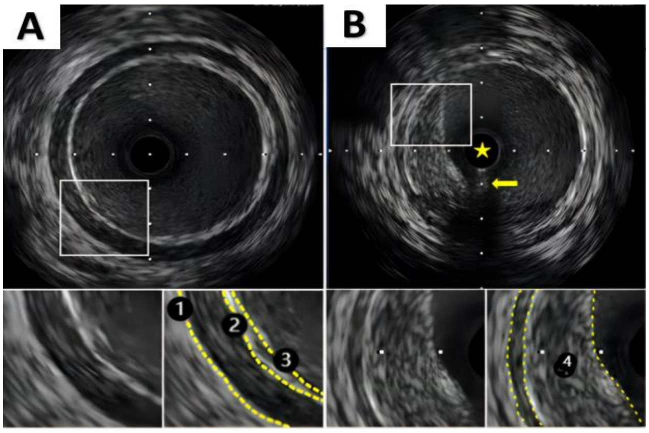

Figure 2: IVUS Images of the Superficial Femoral Artery

Notes: A. Normal superficial femoral artery; B. Diseased superficial femoral artery. 1. Adventitia; 2. Media; 3. Endothelium; 4. Atherosclerotic plaque.

The asterisk* indicates the IVUS catheter; the arrow indicates the guidewire with an acoustic shadow.

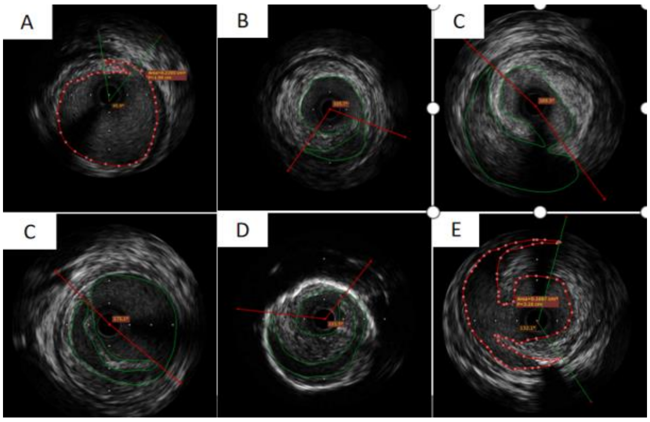

Figure 3: Dissection Classification

Notes: A. Cross-sectional IVUS image showing arterial dissection; B. Classification by depth: Type A (confined to the intima), Type B (extends to the media), Type C (reaches the adventitia); C. Classification by angle: Type 1 (<180°), Type 2 (≥180°); D. Dissection area measurement for quantitative evaluation.

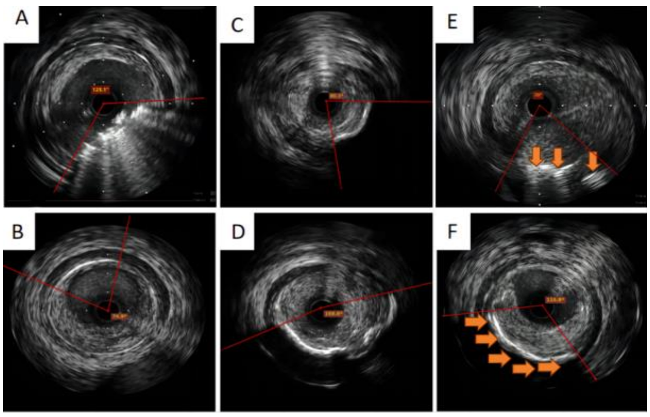

Figure 4: Classification of Calcification

Notes: A. A1-type calcification; B. A2-type calcification; C. B1-type calcification; D. B2-type calcification; E. Spotty calcification; F. Circular calcification.

3.2 Quantitative Measurements

3.2.1 Length and Diameter

IVUS accurately measures lesion length and vessel diameter, avoiding projection errors inherent in angiography. This precision supports optimal stent sizing and placement, reducing procedural complications [15][16].

3.2.2 Lumen and Plaque Burden

IVUS quantifies lumen dimensions (area, minimum / maximum diameters) and plaque burden, critical for assessing lesion severity and treatment efficacy. In peripheral arteries, plaque volume is calculated by subtracting lumen area from IEM area [17][18].

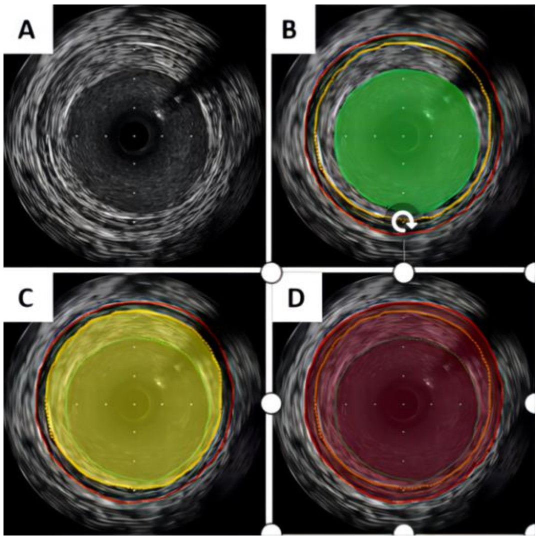

Figure 5: Measurement of Lumen, IEM, and EEM Areas

Notes: A. IVUS image showing an atherosclerotic plaque; B. Lumen area measured from the intima-lumen boundary; C. IEM area measured from the intima-media boundary; D. EEM area measured from the media-adventitia boundary.

3.2.3 Stent Assessment

Post-stenting, IVUS evaluates stent expansion, apposition, and symmetry. Poor apposition or compression can lead to restenosis, necessitating corrective measures like balloon dilation [19][20].

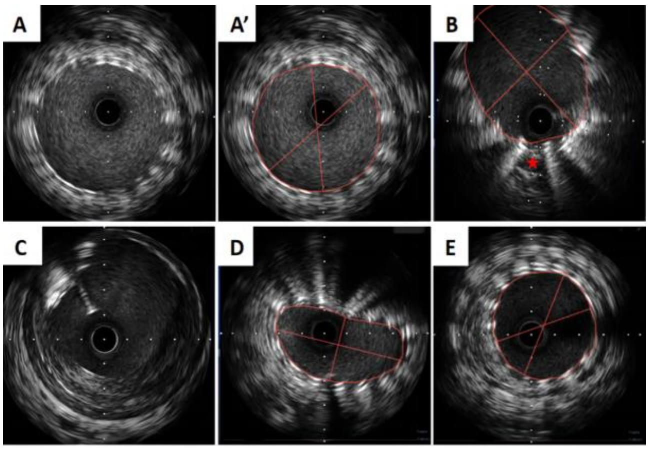

Figure 6: Stent Implantation and Calcification

Notes: A. Stent area measured by identifying the leading edge of stent struts; A' shows good stent apposition; B. Poor stent apposition, indicated by blood flow between stent struts and the vessel wall (marked with an asterisk); C. Calcification appears as bright echoes with posterior shadowing, potentially causing reverberation or multiple reflections; D. Uneven stent compression; E. Uniform stent compression.

3.2.4 Guidewire Positioning

IVUS is instrumental in guiding wires during complex interventions, particularly in chronic total occlusions (CTOs). It confirms wire location in the true lumen, reducing procedural risks and enhancing success rates [21][22].

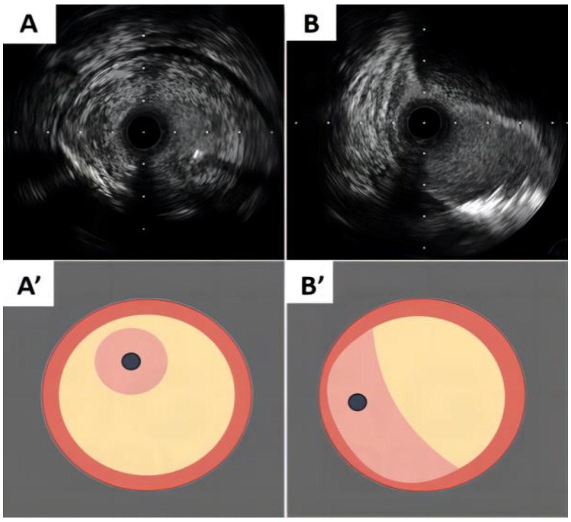

Figure 7: Ultrasound Catheter Positioning and Plaque Distribution

Notes: A: The ultrasound catheter is positioned in the true lumen, with plaques evenly distributed along the vessel wall; B: The ultrasound catheter is positioned in the subintimal space, resulting in poor lumen acquisition. Dark pink: Represents the media (middle layer of the vessel wall); Yellow: Indicates plaque distribution; Light pink: Denotes the vascular lumen.

3.3 Real-World Evidence

In the post-treatment phase, IVUS plays a critical role in monitoring stent patency and identifying complications such as in-stent restenosis or neointimal hyperplasia. Its ability to provide high-resolution three-dimensional imaging surpasses traditional angiography, allowing clinicians to detect poorly apposed or compressed stents—key contributors to thrombosis risk. Quantitative metrics, including cross-sectional stent area and symmetry index, are invaluable for assessing procedural success and guiding subsequent treatments. Real-world studies and clinical trials consistently underscore IVUS's clinical efficacy and safety in lower extremity arterial interventions. For example, IVUS-guided procedures significantly reduce restenosis rates and procedural complications compared to angiography. Large-scale trials, such as those led by Jaff et al. , demonstrate a marked reduction in major adverse cardiovascular events (MACE) and improved long-term vessel patency in IVUS-guided stenting. Furthermore, domestic multi-center studies corroborate these findings, highlighting higher rates of vessel patency and lower restenosis rates in IVUS-guided interventions. Collectively, these data validate IVUS as an indispensable tool for optimizing therapeutic outcomes and advancing the precision of lower extremity arterial treatments [23-26].

3.4 Challenges and Limitations of IVUS

Despite its significant advantages in the treatment of lower extremity arterial disease, intravascular ultrasound (IVUS) faces several challenges that limit its broader clinical adoption. These challenges include operational complexity, high costs, and technical limitations. The requirement for specialized training and expertise makes IVUS less accessible in regions with limited medical resources [6][13]. Additionally, the cost of IVUS equipment and procedures remains a barrier to widespread use, particularly in resource-constrained settings [18].

Technical limitations further complicate IVUS application. Its resolution, while high, may be insufficient for identifying small or superficial lesions [7][16]. Artifacts such as non-uniform rotational distortion (NURD) and ring-down effects can degrade image quality, leading to potential diagnostic inaccuracies [15]. Moreover, the size and rigidity of IVUS catheters may pose challenges when navigating severely narrowed or highly tortuous vessels, increasing the risk of procedural complications [10][13].

To address these limitations, ongoing advancements in IVUS technology are expected to enhance its capabilities and accessibility. Integration with artificial intelligence (AI) holds significant promise, offering automated image analysis, improved image quality, and reduced operational complexity [27]. AI-driven systems can also minimize subjective interpretation errors and streamline workflows, making IVUS more user-friendly and efficient [6].

Another promising development is the emergence of all-optical IVUS (AO-IVUS), which provides higher resolution and better imaging depth compared to traditional systems. This innovation could overcome current limitations in visualizing complex vascular structures and improve diagnostic precision [14]. Additionally, combining IVUS with other imaging modalities, such as optical coherence tomography (OCT) or magnetic resonance imaging (MRI), may offer comprehensive insights into vascular pathology, enhancing decision-making in complex cases [9][27].

Future IVUS devices are also anticipated to be smaller, more flexible, and capable of navigating challenging anatomical regions. These advancements, coupled with fully automated IVUS systems, could simplify image acquisition, processing, and interpretation. Such innovations would lower the learning curve for clinicians and reduce procedural time, broadening IVUS adoption in diverse healthcare settings [23][24].

In summary, while IVUS currently faces operational, financial, and technical challenges, technological advancements are poised to transform its clinical utility. With AI integration, enhanced imaging systems, and device miniaturization, IVUS is set to become a more accessible, precise, and indispensable tool in the treatment of lower extremity arterial disease, significantly improving patient outcomes and expanding its role in vascular medicine [26][28].

3.5 Comparative Analysis with Other Imaging Techniques

In the field of vascular imaging, various techniques offer distinct advantages and limitations. A comparative summary of intravascular ultrasound (IVUS), computed tomography angiography (CTA), magnetic resonance angiography (MRA), and optical coherence tomography (OCT) is provided in Table 1 to facilitate an understanding of their respective roles in clinical practice [5][13-14][29-32].

Table 1: Comparative Analysis of Imaging Techniques

Imaging Technique	Advantages	Limitations	Applications
IVUS	Real-time imaging, high resolution, detailed plaque analysis, procedural guidance.	Invasive, operator-dependent, costly, requires catheter-based operation.	Guiding complex interventions, stent assessment, detailed plaque morphology evaluation.
CTA	Non-invasive, rapid imaging, high spatial resolution, ideal for acute settings.	Requires iodinated contrast, radiation exposure, artifacts from severe calcifications.	Anatomical evaluation, pre-procedural planning, acute vascular event diagnosis.
MRA	No radiation, suitable for contrast-allergic or renal-impaired patients, good soft tissue visualization.	Lower resolution, motion artifacts, prolonged imaging time, limited with metallic implants.	Long-segment lesion imaging, monitoring chronic arterial diseases, suitable for vulnerable patients.
OCT	Ultra-high resolution for superficial structures, ideal for coronary microarchitecture.	Limited penetration depth, requires blood clearance, not suitable for large or calcified vessels.	Coronary artery interventions, stent deployment, assessing high-risk plaque features.

4. Conclusion

Intravascular ultrasound (IVUS) has demonstrated significant value in the diagnosis and treatment of lower extremity arterial diseases by providing high-resolution imaging of vascular structures and lesions [33][34]. IVUS enables precise assessment of lesion characteristics, vessel wall conditions, and treatment outcomes, offering critical guidance for endovascular therapy. Clinical studies have consistently shown that IVUS-guided procedures result in lower restenosis rates, reduced complications, and improved long-term vessel patency compared to conventional imaging techniques [35].

Despite its advantages, IVUS adoption faces challenges such as high costs, operational complexity, and susceptibility to imaging artifacts [34]. However, advancements in artificial intelligence (AI), optical IVUS, and miniaturized device technologies hold the potential to overcome these limitations [36][37]. These innovations will not only enhance diagnostic accuracy and efficiency but also expand IVUS applications to more complex vascular conditions and resource-constrained settings.

In the future, as IVUS technology becomes more integrated with AI and multimodal imaging approaches, it is expected to play an increasingly vital role in the management of peripheral artery disease. By improving the precision and safety of endovascular interventions, IVUS will contribute to better patient outcomes and reduced healthcare burdens globally.

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Author Profile

Xinyi Li born in 1999 in Sichuan, is currently a master's degree candidate at Chongqing Medical University, specializing in peripheral vascular diseases. He is pursuing a master's degree related to peripheral vascular diseases at Chongqing Medical University. Contact: Email: lxy518918@163.com.