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Artificial Intelligence And Advanced Vascular Imaging: Emerging Tools For Precision In Peripheral Arterial Disease Management

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ABSTRACT

Background: Peripheral arterial disease (PAD) is a growing global health issue, often underdiagnosed due to limitations in conventional imaging. Artificial intelligence (AI) offers new opportunities to improve PAD diagnosis and management.

Methods: This review summarizes recent advances in vascular imaging—such as duplex ultrasound, CTA, MRA, and intravascular modalities—and the integration of AI methods like machine learning and deep learning to enhance image interpretation and clinical decision-making.

Results: AI has shown high accuracy in detecting PAD lesions, automating plaque assessment, and predicting outcomes. These tools can match or exceed expert performance, yet real-world implementation faces barriers, especially in low-resource settings.

Conclusions: AI-enhanced imaging has strong potential to transform PAD care through more accurate, personalized diagnosis and treatment. Broader adoption will require addressing technical, regulatory, and infrastructure challenges.

Keywords: *Peripheral Arterial Disease, Artificial Intelligence, Vascular Imaging, Machine Learning*

1. INTRODUCTION

Peripheral artery disease (PAD) is a common atherosclerotic condition and a growing global health burden. It affects over 230 million people worldwide and has been identified as a major cause of cardiovascular morbidity and mortality, with five-year cardiovascular mortality rates in PAD patients approaching 15–20%. The global prevalence of PAD has increased markedly over the past few decades – nearly doubling since 1990 – driven by population aging and the widespread persistence of risk factors. Despite its prevalence and clinical significance, PAD often remains underdiagnosed and insufficiently managed, frequently being recognized only at advanced stages due to low patient awareness and a high proportion of asymptomatic or atypical presentations. This gap in early detection and treatment underscores the need for more precise diagnostic and management strategies in PAD (1,2).

In recent years, advanced vascular imaging modalities and artificial intelligence (AI) techniques have emerged as promising tools to enhance the precision of PAD diagnosis and management. Modern imaging methods such as duplex ultrasound, CT angiography (CTA), and MR angiography provide detailed visualization of peripheral arteries, and AI-driven analysis can further augment these modalities by automating image interpretation. For example, machine learning algorithms have been developed to automatically detect and characterize arterial lesions on imaging studies (e.g. Doppler ultrasound or CTA), which can facilitate earlier PAD detection and assist in treatment planning. Such AI-based image analysis has demonstrated potential to improve screening efficiency, enhance diagnostic accuracy, and streamline pre-surgical planning in PAD care. Beyond diagnosis, AI-driven predictive models are being applied to integrate imaging findings with clinical data, enabling risk stratification and prognostication – for instance, estimating disease progression or amputation risk – to support personalized therapeutic decision-making. These emerging applications of AI in vascular imaging collectively aim to augment clinical decision-making and improve patient outcomes, heralding a new era of precision medicine in PAD management (1,3).

2. PERIPHERAL ARTERIAL DISEASE (PAD): CLINICAL BURDEN AND IMAGING NEEDS

Peripheral arterial disease (PAD) imposes a substantial global health burden. In 2015, an estimated 236 million adults worldwide (about 5.6% of those aged 25 years and older) were living with PAD. Demographic shifts and the growing prevalence of risk factors have driven further increases in PAD incidence, making it one of the fastest rising cardiovascular conditions. The disease is strongly age-related and shares risk factors with coronary and cerebrovascular atherosclerosis (particularly cigarette smoking and diabetes mellitus). Notably, over 70% of individuals with PAD reside in low- and middle-income countries, where limited awareness and resources contribute to underdiagnosis and suboptimal management of this condition(4,5).

The burden of PAD is particularly high in Asia. Among World Health Organization regions, the Western Pacific (which includes East Asia) harbors the greatest number of PAD cases (~74 million), whereas the Eastern Mediterranean has the fewest (~15 million). Indeed, just 15 countries account for over two-thirds of global PAD cases, with China and India alone contributing the largest shares(4). Prevalence estimates in parts of Asia also exceed those reported in Western populations; for example, a recent meta-analysis found PAD prevalence to be approximately 14.5% in South Asia, compared to about 5–6% in North America(6). This regional disparity reflects Asia's large at-risk population alongside rising rates of diabetes, smoking, and other atherogenic factors that drive PAD incidence.

Southeast Asia exemplifies the significant and growing PAD burden in the developing world. As of 2010, roughly 54.8 million people in Southeast Asian countries were living with PAD, a figure that has likely grown substantially over the past decade (7). Some evidence suggests that PAD in this region tends to manifest at relatively younger ages – with many cases reported in individuals under 55 years old – unlike the older age profile typical of high-income countries(8). The high prevalence of diabetes and smoking in Southeast Asian populations may contribute to earlier onset and aggressive progression of PAD. However, epidemiological data from many low-resource settings (including parts of Southeast Asia) remain limited, underscoring the need for further population-based research(4).

Despite the sizeable disease burden, early diagnosis of PAD remains challenging. A large proportion of patients do not present with classic claudication; many are asymptomatic or have atypical leg symptoms, leading to under-recognition in clinical practice(4). Routine screening with the ankle–brachial index (ABI) in primary care is underutilized, and even when performed, the ABI can be falsely normal in patients with long-standing diabetes due to medial arterial calcification. Moreover, diabetic neuropathy may mask ischemic leg pain, further delaying the recognition of PAD (9). As a result, PAD is often underdiagnosed and undertreated worldwide, with many patients first identified at advanced stages such as chronic limb-threatening ischemia(7).

Conventional vascular imaging modalities are essential for PAD diagnosis and treatment planning, but each has important limitations. Duplex ultrasonography is a first-line, noninvasive tool that provides hemodynamic information without radiation; however, it is highly operator-dependent, time-intensive, and has a limited field of view, especially in the presence of arterial calcification that causes acoustic shadowing. Computed tomography angiography (CTA) offers detailed three-dimensional visualization of the arterial tree, yet it requires ionizing radiation and iodinated contrast exposure, and its diagnostic accuracy diminishes with heavy calcification or in small distal vessels. Magnetic resonance angiography (MRA) yields high-contrast images without X-rays, but standard contrast-enhanced MRA cannot be used in many patients with renal dysfunction due to the risk of nephrogenic systemic fibrosis from gadolinium agents. Finally, catheter-based digital subtraction angiography (DSA) remains the diagnostic gold standard for delineating peripheral lesions; it is invasive and carries risks from arterial puncture, contrast nephrotoxicity, and radiation, and it provides only a two-dimensional luminogram of the vessel lumen. These limitations in current imaging approaches highlight the need for more advanced vascular imaging techniques – potentially enhanced by artificial intelligence – to improve the detection, characterization, and overall management of PAD(10).

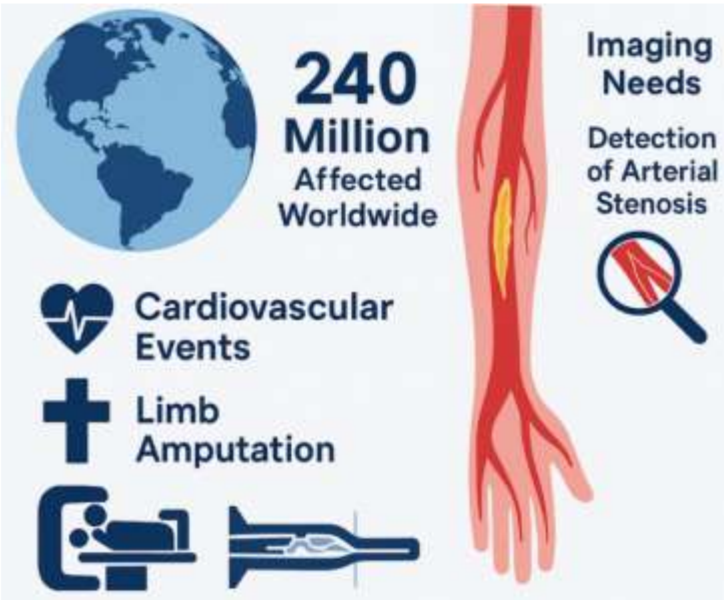

Figure 1. Global Burden of Peripheral Arterial Disease

3. ADVANCES IN VASCULAR IMAGING MODALITIES

Peripheral arterial disease (PAD) management has benefited from significant advances in noninvasive vascular imaging over the past few years. For initial assessment, duplex ultrasound (DUS) remains a frontline tool due to its safety, low cost, and effectiveness in detecting plaques and grading stenoses(11). Recent adjuncts to ultrasound, such as elastography, can map arterial wall stiffness and potentially differentiate plaque types, thus enhancing the diagnostic value of ultrasonography in PAD. Computed tomography angiography (CTA) is another widely used modality, offering high-resolution 3D visualization of the arterial tree from the aorta to the foot in a single, quick scan. However, CTA requires ionizing radiation and iodinated contrast, and its accuracy can be limited by heavy arterial calcifications that produce blooming artifacts. To overcome these limitations, newer CT technologies like dual-energy CTA and photon-counting CT have been introduced. These enable improved tissue characterization and reduce calcium artifacts, allowing more reliable detection of significant stenoses at lower radiation doses. Magnetic resonance angiography (MRA) has likewise seen improvements. While conventional contrast-enhanced MRA is highly reliable for mapping PAD extent, its use of gadolinium contrast is a concern in patients with renal impairment. Recent developments such as quiescent-interval single-shot MRA now permit full lower-extremity arterial imaging without any contrast agent. Moreover, advanced MRI sequences (e.g. black-blood imaging and ultrashort echo time techniques) can visualize vessel wall and plaque characteristics (including fibrous tissue and calcifications) that were previously hard to assess. This detailed MRI plaque imaging helps identify lesions with extensive calcium or dense fibrosis, which are known to be harder to cross with guidewires, thereby informing clinicians about potential endovascular challenges (10).

Despite the strides in noninvasive imaging, catheter-based digital subtraction angiography (DSA) remains the diagnostic gold standard for PAD and an indispensable tool during interventions. DSA provides dynamic high-resolution lumen visuals and the opportunity for immediate endovascular treatment, but it is invasive and carries notable limitations (two-dimensional projection only, ionizing radiation exposure, nephrotoxic contrast requirement, and difficulty visualizing through total occlusions). To address these drawbacks, recent innovations have enhanced DSA technology. One example is *digital variance angiography* – a kinetic imaging technique that combines multiple low-dose frames – which has shown improved image quality with lower radiation exposure compared to conventional DSA. Additionally, robotic-assisted angiography systems for peripheral interventions have been developed to increase precision and reduce radiation to operators, potentially streamlining complex PAD revascularizations. Alongside these, intravascular imaging modalities are emerging as valuable adjuncts during PAD procedures. Intravascular ultrasound (IVUS), long used in coronary interventions, has been increasingly adopted in peripheral arteries to accurately determine true lumen diameter, plaque burden, and optimal stent sizing. IVUS provides cross-sectional insight into plaque morphology and stenosis severity that complements the planar view of angiography. Similarly, optical coherence tomography (OCT) has been introduced into lower-extremity interventions, capitalizing on its superior resolution to generate detailed two- and three-dimensional images of the arterial interior. OCT can delineate fine plaque microstructures (e.g. fibrous caps, thrombus, micro-calcifications) and evaluate stent deployment with greater clarity than IVUS. The main trade-off is that OCT requires transient clearance of blood with contrast flush and is generally limited to vessels of <5 mm diameter, yet it offers a unique advantage in identifying plaque features that might influence treatment. These intravascular tools, though requiring an invasive approach, reveal lesion details not visible on angiography alone – for instance, IVUS and high-resolution MRI can measure vessel wall dimensions and calcium distribution that angiograms cannot – thereby refining decision-making for complex lesions and improving procedural precision in PAD management (10).

Beyond the improvements in anatomic imaging, there is a growing emphasis on functional and molecular imaging of PAD to guide precision therapy. Nuclear medicine techniques have advanced to assess limb perfusion and tissue viability in ways not possible with standard angiography. Notably, hybrid single-photon emission CT (SPECT) imaging of the lower extremity can detect microvascular perfusion deficits in the feet of patients with critical limb ischemia. SPECT/CT perfusion scans using tracers like technetium-99m tetrofosmin enable quantification of blood flow in specific foot territories (angiosomes) and have demonstrated prognostic value: patients with greater post-treatment perfusion improvement on SPECT have significantly better limb salvage outcomes than those with poor perfusion responses. Positron emission tomography (PET) is also being explored for its ability to visualize vascular biology in PAD. Tracers such as ^18F-fluorodeoxyglucose (which highlights inflammation) and ^18F-sodium fluoride (which highlights micro-calcification activity) have garnered attention for imaging atherosclerotic disease activity. Early studies suggest that PET can identify inflamed or active plaques in peripheral arteries – for example, elevated ^18F-NaF uptake in femoral artery plaques has been correlated with high-risk patient profiles and cardiovascular risk factors – pointing to a future role of PET as a noninvasive biomarker of plaque vulnerability in PAD (12). Another emerging modality is photoacoustic imaging, which merges optical and ultrasound techniques to assess tissue oxygenation and perfusion in vivo. Multispectral optoacoustic tomography (MSOT), for instance, has recently been applied to measure muscle oxygenation in the calves of PAD patients. One study showed that post-exercise MSOT readings of hemoglobin oxygen saturation in calf muscle could distinguish patients with intermittent claudication from healthy individuals with high sensitivity and specificity (13). Such optoacoustic imaging provides a direct functional readout of ischemic muscle physiology, which may complement traditional angiographic findings. Together, these cutting-edge imaging modalities – from advanced CT/MR innovations to intravascular optics and functional nuclear imaging – are contributing to a more comprehensive and precise evaluation of PAD. By integrating anatomical detail with hemodynamic and biological information, clinicians can better tailor interventions, anticipate complications, and ultimately improve outcomes for patients with PAD (10,12).

4. ARTIFICIAL INTELLIGENCE IN VASCULAR IMAGING: CONCEPTS AND METHODS

Artificial intelligence (AI) in the context of peripheral arterial disease (PAD) imaging refers to the use of computer algorithms to mimic human analytical abilities and automate image interpretation tasks (14). At its core, AI encompasses machine learning (ML) techniques where models learn from data to recognize patterns and make predictions, rather than following fixed programmed rules. ML algorithms improve their performance as they are exposed to more labeled examples, identifying complex relationships within imaging data. Deep learning (DL) is a specialized subset of ML that utilizes multi-layered neural networks to automatically extract and hierarchically integrate features from raw inputs, thereby improving the detection and classification of subtle imaging patterns (15). In vascular imaging, the most prominent DL models are convolutional neural networks (CNNs), which are inspired by biological vision and consist of layered neurons arranged to process visual data. CNNs use convolutional layers to scan imaging inputs and detect local features (e.g. vessel edges or calcifications) and pooling layers to progressively condense information, preserving the most salient features while reducing noise (14). Through this layered feature extraction, CNNs build an internal representation of the vascular image that can be used to identify anatomical structures and pathologies with high fidelity.

These AI models function by learning a mapping from imaging data to clinical outputs through an iterative training process. Typically, a large set of vascular images with ground-truth labels (such as expert-outlined vessels or known diagnoses) is used to train the model in a supervised learning paradigm. During training, the network's parameters are optimized to minimize the error between its predictions and the true labels, enabling the model to "learn" the relevant imaging features that distinguish healthy versus diseased patterns. In a CNN, each successive layer captures increasingly complex features: initial layers might detect simple edges or contrast differences, while deeper layers combine these into motifs like vessel contours or plaque textures. By the final layer, the network can decide whether a specific pattern corresponds to disease or normal anatomy, or it can output a segmentation map highlighting structures of interest. This end-to-end learning approach obviates the need for manual feature engineering and can achieve high accuracy given sufficient training data and computational resources. For instance, modern CNN-based systems can process 3D vascular imaging volumes much faster than human analysis, reducing image interpretation times dramatically (one report noted a reduction from several hours of manual work to minutes of automated processing). Moreover, the consistency of AI-driven analysis can improve reproducibility; a DL model will apply the same criteria to every image, reducing inter-observer variability in tasks such as vessel wall delineation and measurement. As a result, these models can match expert performance in many scenarios, and in some cases their quantitative assessments (e.g. of vessel thickness or plaque volume) correlate strongly with expert readings while also being more reproducible (14).

AI techniques are being harnessed to enhance multiple aspects of vascular imaging for PAD, including segmentation, plaque characterization, and diagnosis. One important application is **automated vessel segmentation**: DL algorithms (usually CNN-based) can delineate arterial structures on imaging modalities like CT angiography or MRI, separating blood vessels from surrounding tissues with high precision. This yields detailed vascular maps and measurements that aid in quantifying disease burden. For example, a recent deep learning model was able to segment the entire lower-extremity arterial tree from the aorta to the legs on CTA scans, achieving a segmentation accuracy comparable to expert manual tracing (Dice coefficient over 0.8). Notably, the same model could also quantify arterial calcifications (an indicator of atherosclerotic plaque burden) along the segmented vessels, with automated calcium scores showing excellent agreement with radiologists' assessments (16). Such **plaque characterization** benefits from AI's ability to detect and classify different tissue patterns within the vessel wall. CNNs can be trained to recognize features of atherosclerotic lesions – for instance, distinguishing calcified plaque regions from soft plaques or normal wall – based on image intensity and texture, which helps in evaluating plaque composition and stability (17). By automatically characterizing plaques on imaging, AI models provide insights into disease severity and potential risk (e.g. identifying high-risk plaque features) that go beyond what simple luminal narrowing measurements offer. In terms of **diagnosis**, ML models assist in identifying and grading PAD lesions from imaging data, supplementing the clinician's decision-making. CNN-based analysis can rapidly flag arterial narrowing or occlusions on angiograms and classify their severity, functioning as a second reader to improve detection of clinically significant disease. For instance, one study reported that a CNN trained on thousands of PAD CTA images could classify arterial stenoses in different vascular segments with over 90% accuracy(15). Similarly, AI algorithms applied to vascular ultrasound and other modalities can detect abnormal patterns (such as altered flow waveforms or plaque appearance) that indicate PAD, thus supporting earlier and more reliable diagnosis (17). By automating segmentation, refining plaque assessment, and improving lesion detection, artificial intelligence serves as an emerging tool to increase the precision of PAD imaging. These methods bolster the clinician's ability to evaluate peripheral arterial disease more objectively and comprehensively, potentially leading to earlier interventions and personalized treatment strategies guided by detailed AI-driven image analysis.

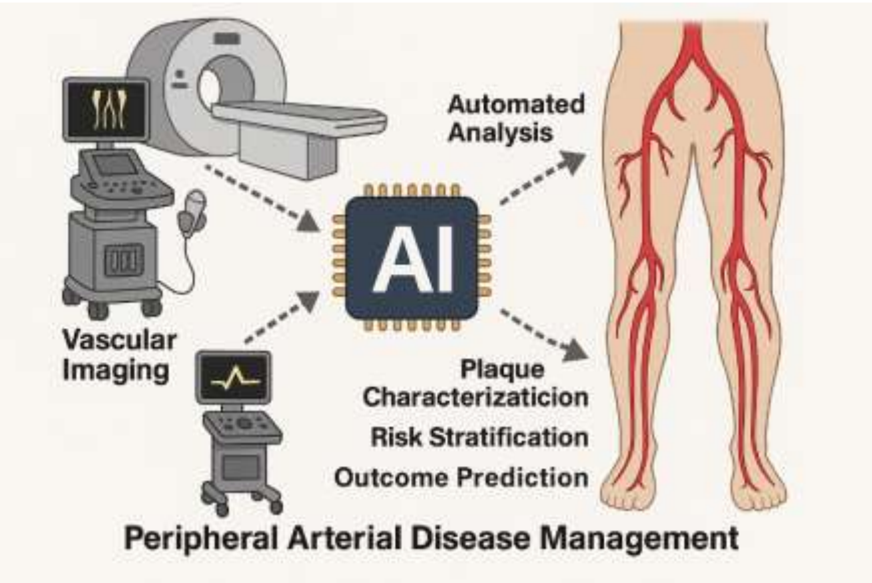

Figure 2. The Role of Artificial Intelligence in Enhancing Vascular Imaging for Peripheral Arterial Disease

5. CLINICAL APPLICATIONS OF AI FOR PAD

Artificial intelligence (AI) techniques are being applied to improve the diagnosis of peripheral arterial disease (PAD), aiming to catch cases earlier and more accurately. In clinical practice, machine learning models have been used to flag PAD patients who might be missed by traditional methods. For example, natural language processing of electronic health records (EHRs) can identify PAD cases with greater accuracy than billing-code based searches (reporting an area under the curve ~0.89 vs ~0.80)(14). AI has also enhanced non-invasive vascular assessments: a recent deep learning model analyzing arterial pulse waveforms (e.g. pulse volume recordings) markedly outperformed the ankle–brachial index for PAD detection (AUC $\geq$0.89 vs $\leq$0.59)(18). Furthermore, computer vision applied to vascular imaging can aid PAD diagnosis. One study trained a convolutional neural network (CNN) to interpret Doppler ultrasound waveforms and accurately localize arterial occlusions, achieving high diagnostic performance (F1-scores ~0.91–0.98 for detecting disease in various segments). Similarly, a CNN system for automatic interpretation of peripheral CT angiography was able to classify stenosis severity with over 90% accuracy – approaching expert radiologist performance – using digital subtraction angiography as the reference standard. These advances suggest that AI can increase the sensitivity and consistency of PAD screening and diagnostic imaging in clinical settings (14).

Beyond diagnosis, AI is being leveraged to support treatment decision-making in PAD, such as determining when an intervention (revascularization) is warranted versus continued conservative therapy. Machine learning–based risk stratification tools can integrate diverse clinical data to guide these choices. For example, a predictive model combining patient clinical factors with a panel of biomarkers was shown to detect angiographically significant PAD with high accuracy (AUC ~0.85) and was proposed as a "gatekeeper" for invasive angiography – effectively identifying which patients might benefit from revascularization(14). Another group employed a random forest algorithm using standard laboratory and exam parameters to distinguish advanced, limb-threatening ischemia from milder claudication; the ML-generated score correlated with low ankle–brachial index values and signaled an urgent need for vascular intervention(18). Such tools illustrate how AI can synthesize multiple risk indicators to assist clinicians in triaging PAD patients and personalizing therapy. Unsupervised machine learning has likewise been used to reveal distinct PAD phenotypes (clusters of patients with differing profiles), information that could be leveraged to tailor treatment strategies to the needs and risks of each subgroup(14). In the future, these data-driven approaches may help optimize decisions like the choice between endovascular versus open surgery or the intensity of medical therapy for PAD, by predicting which strategy would yield the best outcome for a given patient.

AI-driven prognostic models are also emerging as valuable tools in PAD management, helping predict outcomes and thus inform long-term care plans. One application is cardiovascular risk stratification in PAD patients: for instance, machine learning analysis of EHR data was able to predict future major adverse cardiovascular events (e.g. myocardial infarction or stroke) in PAD cohorts, improving identification of high-risk patients who may need aggressive preventive measures. Similarly, AI can extract prognostic biomarkers from routine imaging; an automated analysis of screening CT scans quantified arterial calcification and other features to predict 5-year cardiovascular risk more accurately than the Framingham risk score (14). In terms of limb prognosis, researchers have developed models to forecast which PAD patients are likely to experience limb loss or other major limb events. Notably, a recent study using preoperative clinical data and ML algorithms achieved excellent discrimination (AUROC ~0.93) for predicting 30-day major adverse limb events or death after endovascular therapy, far outperforming a traditional risk model (logistic regression AUC ~0.72)(19). More broadly, a 2023 systematic review found numerous ML models that predict amputation risk with good to excellent performance (some with AUCs ~0.8–0.9), underscoring their potential to surpass conventional risk scoring and clinical judgment. However, many of these predictive models are still in early stages, with some limited by small sample sizes or other biases, so further validation is needed before they are fully integrated into practice(20). Overall, the growing body of evidence suggests that AI can provide clinically useful predictions in PAD – from cardiovascular event risk to likelihood of limb salvage – enabling more precise, individualized management of the disease.

6. WORKFLOW INTEGRATION AND REAL-WORLD CHALLENGES

Integrating AI-driven vascular imaging into routine PAD care faces significant global barriers. A foremost issue is data quality: many AI models lack access to large, diverse, and high-quality datasets, limiting their robustness and generalizability . Inadequate technical infrastructure and poor interoperability of systems can hinder seamless workflow integration of AI tools, often requiring costly workflow redesigns or new equipment. Clinician adoption also remains a challenge, as the opaque "black-box" nature of some algorithms diminishes trust and can trigger resistance from practitioners who are unaccustomed to AI-driven decision support. Clear regulatory and legal frameworks are still evolving; uncertainty around approvals, liability, and data governance creates hesitation in deploying AI clinically (21). Indeed, recent surveys of health system leaders echo these concerns, citing regulatory issues, data security/integration problems, workflow disruption, and low clinician acceptance as principal obstacles to AI adoption in healthcare (22).

In Southeast Asia, these challenges are amplified by regional resource disparities and disease-specific issues. Many countries in this region have limited digital health infrastructure, with health data often siloed across incompatible platforms that impede data sharing and AI implementation (23). There is considerable variability in patient demographics and care practices across Southeast Asian populations, as evidenced by differing PAD epidemiology and access to diagnostics, which means AI models and guidelines developed elsewhere may not directly translate to local contexts. Compounding these issues, peripheral arterial disease is widely underdiagnosed and undertreated in this region. An estimated 54.8 million individuals in Southeast Asia were living with PAD in 2010, yet low awareness and limited screening contribute to many cases remaining undetected(7). This under-recognition leads to smaller datasets and a reduced impetus for clinicians to embrace new AI-driven diagnostic tools, creating a cycle in which both data and adoption remain limited in real-world PAD management.

7. CONCLUSION

The integration of artificial intelligence with advanced vascular imaging represents a transformative development in the diagnosis, treatment planning, and prognostic evaluation of peripheral arterial disease (PAD). By enabling automated segmentation, plaque characterization, risk stratification, and outcome prediction, AI-driven technologies address key limitations in conventional imaging and support a shift toward precision medicine in PAD management. Although significant advances have been made, real-world implementation faces challenges including data quality, clinical validation, and system integration—especially in resource-limited regions such as Southeast Asia. Continued multidisciplinary collaboration and regional adaptation of AI tools are essential to realize their full clinical potential and ensure equitable improvements in PAD care.

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