Artificial intelligence-enhanced vascular access in hemodialysis – challenges and innovations

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Background

Vascular access represents the lifeline for patients undergoing hemodialysis, yet its management faces dual challenges: a global shortage of specialized surgical workforce and high rates of access dysfunction. This review examines the intersection of artificial intelligence (AI) applications in vascular access surveillance and innovative workforce solutions addressing global surgical shortages.

Methods

A comprehensive narrative review was conducted synthesizing evidence from randomized controlled trials, observational studies, and international guidelines. Literature was identified from PubMed, Scopus, and Web of Science, with emphasis on publications from 2020 to 2025 addressing AI-based vascular access surveillance algorithms and task-shifting workforce models in hemodialysis.

Results

Machine learning algorithms demonstrated promising results in predicting arteriovenous fistula and graft stenosis through analysis of hemodynamic parameters, ultrasound imaging, and electronic health record integration. Convolutional Neural Networks and deep learning models achieve sensitivity and specificity exceeding 90% in detecting early access dysfunction, potentially reducing thrombosis events and catheter dependence. Concurrently, the global nephrology community confronts critical shortages of vascular surgeons, particularly in low-income and middle-income countries, where permcath dependence rates exceed 70% in some regions. Task-shifting models involving nephrologist-performed catheter insertions and maintenance procedures demonstrated safety profiles comparable to traditional surgical approaches, with technical success rates of 95-98%.

Conclusions

An integrated framework combining AI-enhanced surveillance with workforce development strategies offers a promising pathway to optimize vascular access outcomes. Implementation challenges in resource-limited settings require scalable technologies, adapted training models, and supportive policy. As the global burden of end-stage kidney disease continues to rise, this dual approach represents a transformative strategy to reduce morbidity associated with access dysfunction.

Keywords:

arteriovenous fistula, artificial intelligence, clinical decision support, global health, hemodialysis, machine learning, predictive modeling, task-shifting, vascular access, workforce development

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Introduction

End-stage kidney disease (ESKD) represents a global health challenge of increasing magnitude, with the number of patients requiring kidney replacement therapy projected to double to 5.4 million by 2030 [1]. Hemodialysis remains the predominant modality of renal replacement therapy worldwide, with ~69% of the global dialysis population dependent on this life-sustaining treatment [2]. Central to the delivery of effective hemodialysis is a functioning vascular access, aptly described as the "lifeline" for patients undergoing this therapy. Despite technological advances in dialysis delivery, vascular access dysfunction persists as the leading cause of morbidity, hospitalization, and healthcare expenditure among the hemodialysis population [3,4].

The global nephrology community currently faces a dual challenge in vascular access management. First, the creation and maintenance of optimal vascular access – preferably arteriovenous fistulas (AVFs) or arteriovenous grafts (AVGs) – requires specialized surgical expertise that is increasingly scarce, particularly in low-income and middle-income countries (LMICs) [5]. This workforce shortage has led to concerning trends, including extended waiting times for access creation, increased reliance on central venous catheters, and suboptimal outcomes for patients initiating dialysis [6]. Second, even when successfully created, vascular access dysfunction occurs frequently, with primary patency rates for AVFs and AVGs at 1 year ranging from 60 to 65% and 40 to 50%, respectively [7,8]. Traditional surveillance methods have demonstrated limited efficacy in predicting access failure, highlighting the need for more sophisticated approaches to early detection and intervention [9].

Recent advances in artificial intelligence (AI) and machine learning (ML) technologies have created unprecedented opportunities to address these challenges. AI algorithms capable of analyzing complex datasets – including hemodynamic parameters, ultrasound imaging, and electronic health record (EHR) data – have demonstrated promising results in predicting vascular access dysfunction before clinical manifestations become apparent [10–12]. Concurrently, innovative workforce solutions, including task-shifting models that enable nephrologists to perform certain vascular access procedures, have emerged as potential strategies to address surgical workforce shortages [13,14].

This comprehensive review examines the intersection of these two critical domains: AI-enhanced vascular access surveillance and global strategies for addressing surgical workforce shortages in hemodialysis. By synthesizing evidence from randomized controlled trials, observational studies, and international guidelines, we aim to provide a framework for integrating technological innovation with workforce development to optimize vascular access outcomes globally. The review is structured to address: (a) the global epidemiology of vascular access types and delays; (b) current surveillance methods and their limitations; (c) AI algorithms for predictive modeling in vascular access; (d) task-shifting models for vascular access creation and maintenance; (e) training and credentialing pathways for nephrologists; and (f) implementation challenges in resource-limited settings.

As the global burden of ESKD continues to rise, particularly in regions with limited healthcare resources, this dual approach offers a promising pathway to optimize vascular access outcomes and reduce the morbidity associated with access dysfunction. By leveraging technological innovation while simultaneously addressing workforce constraints, the nephrology community has an opportunity to transform vascular access care and improve the lives of millions of patients dependent on hemodialysis worldwide.

Global epidemiology of vascular access types and delays

Vascular access patterns demonstrate significant global variation, reflecting disparities in healthcare resources, surgical expertise, and clinical practice guidelines. In high-income countries (HICs), there has been a concerted effort to increase AVF utilization following the “fistula first” initiative, with current prevalence rates ranging from 60 to 80% in Europe, Japan, and Australia [15]. The United States has historically lagged behind other developed nations, though recent data indicate improvement with AVF rates approaching 65% [16]. In contrast, LMICs face substantial challenges in achieving optimal vascular access distribution, with central venous catheter dependence rates exceeding 70% in some regions of Africa, Southeast Asia, and Latin America [17].

The global disparity in vascular access types correlates directly with the availability of specialized surgical workforce. A comprehensive international survey conducted across 154 countries revealed that the density of vascular surgeons per million population ranges from 0.1 in low-income countries to 8.4 in HICs [18]. This workforce shortage translates to significant delays in AVF creation, with median waiting times of 6–8 weeks in HICs extending to 6–12 months in many LMICs [19]. The consequences of these delays are profound, with studies consistently demonstrating that late referral for vascular access creation is associated with increased catheter dependence, higher infection rates, and elevated mortality [20].

The burden of ESKD is growing disproportionately in regions with limited healthcare resources. Projections indicate that by 2030, over 70% of patients requiring kidney replacement therapy will reside in LMICs [1]. This demographic shift presents an urgent challenge for vascular access planning, as these regions simultaneously face the greatest workforce constraints. In sub-Saharan Africa, for example, the ratio of nephrologists to ESKD patients can be as low as 1: 500, with even fewer vascular surgeons available for access creation [21].

Socioeconomic factors further compound access disparities within countries. Even in HICs, studies have demonstrated that patients of lower socioeconomic status, racial minorities, and those in rural areas experience longer waiting times for AVF creation and higher rates of catheter-based dialysis initiation [22]. These disparities persist despite evidence that optimal vascular access is associated with reduced morbidity, mortality, and healthcare costs across all patient populations [23].

The economic implications of vascular access type are substantial. Catheter-dependent hemodialysis is associated with increased hospitalization rates, primarily due to infectious complications, with annual costs exceeding $20 000 per patient compared to

AVF-based dialysis [24]. In resource-limited settings, these additional costs can be catastrophic, both for healthcare systems and for patients who often bear significant out-of-pocket expenses [25].

Recent global initiatives have attempted to address these disparities through collaborative efforts between international nephrology societies, surgical organizations, and healthcare policymakers. The International Society of Nephrology's "Saving Young Lives" program has incorporated vascular access training into its capacity-building efforts in LMICs, while the Kidney Disease Improving Global Outcomes guidelines have emphasized the importance of early access planning regardless of resource setting [26,27].

The 2019 Kidney Disease Outcomes Quality Initiative Vascular Access Guidelines represent a paradigm shift in access planning, moving away from a "one size fits all" approach to a more individualized strategy based on patient characteristics, life expectancy, and available resources [28]. This patient-centered approach, termed the "ESKD Life-Plan," acknowledges the global diversity in access practices and encourages optimization within local constraints rather than adherence to rigid targets.

Despite these advances, significant challenges remain in achieving equitable global distribution of optimal vascular access. Innovative approaches to workforce development, including task-shifting models and telehealth consultation, offer potential solutions to address surgical shortages in underserved regions. Concurrently, technological advances in vascular access surveillance may help optimize outcomes for existing access, reducing the burden on limited surgical resources through early intervention and prolonged access survival.

Current surveillance methods and their limitations

Vascular access dysfunction remains the leading cause of morbidity and hospitalization among hemodialysis patients, accounting for ~30% of all admissions in this population [3]. Early detection of access dysfunction through effective surveillance is critical for timely intervention, yet current methodologies demonstrate significant limitations in predictive accuracy and clinical utility. This section examines established surveillance techniques and their constraints, providing context for the potential advantages of AI-enhanced approaches.

Physical examination

Physical examination represents the most accessible surveillance method, involving inspection, palpation, and auscultation of the vascular access. When performed by experienced practitioners, physical examination demonstrates sensitivity and specificity of 80–85% for detecting significant stenosis [29]. The technique relies on identifying characteristic findings, including abnormal thrill, bruit changes, prolonged bleeding postdialysis, and difficult cannulation [30]. Despite its accessibility, physical examination is inherently subjective, with significant interobserver variability and dependence on examiner expertise. In settings with high patient-to-provider ratios or limited specialist availability, the quality and frequency of physical examinations may be compromised, reducing their effectiveness as a surveillance tool [31].

Dynamic venous pressure monitoring

Dynamic venous pressure (DVP) monitoring during dialysis was among the earliest surveillance techniques implemented in routine practice. This method measures resistance to blood flow through the vascular access, with elevated pressures potentially indicating outflow stenosis. However, multiple factors confound DVP measurements, including needle gauge, needle position, blood pump speed, and access flow rate. A systematic review of 12 studies evaluating DVP monitoring found poor predictive value for access thrombosis, with positive predictive values ranging from 30 to 65% [32]. Contemporary dialysis machines incorporate DVP monitoring, but its utility as a standalone surveillance tool is limited by these confounding variables and poor standardization across centers.

Access flow measurement

Access flow measurement has emerged as the most widely studied surveillance technique, with multiple methodologies available including ultrasound dilution, thermal dilution, and ionic dialysance [33]. The principle involves measuring blood flow through the access, with declining flow rates (typically <600 ml/min for AVFs and <800 ml/min for AVGs) or significant decreases from baseline (>20–25%) suggesting stenosis [34]. While access flow measurement demonstrates superior predictive value compared to DVP monitoring, with sensitivity of 60–85% for detecting significant stenosis, several limitations persist. The technique requires specialized equipment, trained personnel, and adds time to dialysis sessions. Furthermore, measurements exhibit considerable variability based on cardiac output, hydration status, and measurement technique [35].

Duplex ultrasound

Duplex ultrasound combines B-mode imaging with Doppler flow analysis, providing anatomical and functional assessment of vascular access. This technique can identify stenosis, measure access flow, and evaluate surrounding tissues for complications such as aneurysm formation or infection. With sensitivity and specificity exceeding 90% for detecting significant stenosis when performed by experienced sonographers, duplex ultrasound represents a comprehensive surveillance tool [36]. However, implementation is constrained by equipment costs, time requirements (20–30 min per examination), and dependence on operator expertise. In resource-limited settings, these constraints often render routine ultrasound surveillance impractical [37].

Recirculation measurement

Access recirculation occurs when dialyzed blood reenters the dialyzer without systemic circulation, reducing treatment efficiency. While recirculation exceeding 10% may indicate access dysfunction, this finding typically occurs late in the stenosis process, limiting its utility for early detection [38]. Modern dialysis machines incorporate online recirculation monitoring, but the technique demonstrates poor sensitivity (30–50%) for detecting access stenosis before critical narrowing occurs [39].

Evidence for surveillance efficacy

Despite widespread implementation of surveillance programs, evidence for their efficacy in improving clinical outcomes remains controversial. The Kidney Disease Outcomes Quality Initiative guidelines acknowledge this uncertainty, noting that while surveillance may detect stenosis, the impact on thrombosis rates, access longevity, and patient outcomes is less clear [28]. A Cochrane systematic review of 14 randomized controlled trials evaluating vascular access surveillance found no significant reduction in access thrombosis or failure rates compared to clinical monitoring alone [9]. This discrepancy between stenosis detection and clinical outcomes suggests that current surveillance approaches may identify abnormalities without effectively distinguishing those requiring intervention from those that may remain stable or resolve spontaneously.

Implementation challenges

Beyond efficacy concerns, implementation of comprehensive surveillance programs faces substantial challenges, particularly in resource-limited settings. These include:

(1) Workforce constraints: effective surveillance requires trained personnel for both testing and interpretation, creating additional burden in settings with limited staff availability.
(2) Equipment costs: specialized devices for access flow measurement and ultrasound imaging represent significant capital investments, often prohibitive in low-resource environments.
(3) Standardization: variability in measurement techniques, interpretation criteria, and intervention thresholds limits comparability across centers and complicates guideline development.
(4) Patient burden: frequent surveillance procedures add time to already lengthy dialysis sessions, potentially affecting quality of life and treatment adherence.

These limitations of current surveillance methodologies highlight the need for more accurate, efficient, and resource-conscious approaches to vascular access monitoring. AI and ML technologies offer potential solutions by integrating multiple data sources, identifying subtle patterns preceding access dysfunction, and providing automated, standardized interpretation accessible across diverse healthcare settings.

Artificial intelligence algorithms for predictive modelling in vascular access

The application of AI and ML to vascular access surveillance represents a paradigm shift in hemodialysis care. These technologies offer the potential to overcome limitations of traditional surveillance methods through enhanced pattern recognition, integration of diverse data streams, and predictive capabilities that extend beyond human analysis. This section examines the evolution, current applications, and emerging evidence for AI-based approaches to vascular access monitoring and dysfunction prediction.

Theoretical foundations and data sources

AI algorithms for vascular access surveillance leverage multiple data sources that collectively provide a comprehensive assessment of access function. These include:

(1) Hemodynamic parameters: dialysis session data including access flow measurements, venous and arterial pressures, recirculation percentages, and ultrafiltration rates contain valuable signals that precede access dysfunction [40].
(2) Imaging data: ultrasound images, both B-mode and Doppler, provide anatomical and functional information about the access. Deep learning algorithms can analyze these images to detect subtle changes in vessel diameter, flow patterns, and wall characteristics that may indicate developing stenosis [41].
(3) EHR data: patient demographics, comorbidities, medication profiles, and laboratory values influence access outcomes and can be incorporated into predictive models to enhance accuracy [42].
(4) Physical examination findings: digitized documentation of access examination, including presence of abnormal thrill, bruit characteristics, and cannulation difficulties, provides additional inputs for comprehensive modeling [43].

(5) Acoustic signals: recent innovations have demonstrated that analysis of blood flow sounds through the access using ML can detect stenosis with high accuracy, offering a low-cost, noninvasive surveillance option particularly suited to resource-limited settings [11].

Machine learning algorithms and their applications

Multiple ML algorithms have been applied to vascular access surveillance, each with distinct advantages and limitations:

Random Forests are ensemble methods that combine multiple decision trees to improve prediction accuracy and reduce overfitting. These algorithms handle mixed data types well and are relatively resistant to noisy data, making them suitable for real-world clinical datasets. Studies have demonstrated sensitivity of 75–85% and specificity of 70–80% for predicting access dysfunction [10].

Support Vector Machines identify optimal boundaries for classification and are particularly effective when training data are limited. Support Vector Machines have shown sensitivity of 80–85% and specificity of 75–85% in predicting AVF failure, with the advantage of requiring relatively modest computational resources [42].

Gradient Boosting methods sequentially build models that focus on correcting errors from previous iterations, often achieving high accuracy. These algorithms have demonstrated sensitivity of 82–88% and specificity of 78–86% for access dysfunction prediction [40].

Convolutional Neural Networks are specialized deep learning architectures designed for image analysis. When applied to ultrasound images of vascular access, Convolutional Neural Networks can automatically extract relevant features and detect stenosis with sensitivity of 85–95% and specificity of 80–90% [41]. However, these models require large training datasets and substantial computational resources.

Recurrent Neural Networks and Long Short-Term Memory networks are designed to capture temporal patterns in sequential data. Applied to longitudinal dialysis session data, these models can identify subtle trends preceding access failure with sensitivity of 85–92% and specificity of 82–89% [43].

Transformer Models represent the latest generation of deep learning architectures, incorporating attention mechanisms that allow the model to focus on the most relevant features. These models can integrate multimodal data (hemodynamic parameters, imaging, EHR data) and have demonstrated sensitivity of 88–94% and specificity of 85–92% for access dysfunction prediction [40].

Clinical evidence and validation studies

Recent studies have provided encouraging evidence for the clinical utility of AI-based vascular access surveillance. A 2024 study by Julkaew *et al.* [10] developed DeepVAQ, an adaptive deep learning model for predicting vascular access quality from photoplethysmography sensors, demonstrating superior performance compared to traditional surveillance methods. Zhou *et al.* [11] reported a deep learning model for automated AVF stenosis screening based on blood flow sounds, achieving area under the curve of 0.91 for detecting significant stenosis.

A large-scale study by Peralta *et al.* [12] developed and validated a ML model predicting AVF failure in a network of dialysis clinics, demonstrating that the model could identify high-risk patients 3–6 months before clinical manifestation of dysfunction. More recently, Shu *et al.* [44] developed an XGBoost model for predicting AVF stenosis risk using clinical data, with SHAP (SHapley Additive exPlanations) analysis enhancing clinical interpretability.

Explainability and clinical integration

A critical challenge in implementing AI-based surveillance is the “black box” nature of many advanced algorithms, which can hinder clinical adoption due to lack of transparency in decision-making [45]. Explainable AI methods, such as SHAP and LIME (Local Interpretable Model-Agnostic Explanations), address this limitation by providing insights into which features most strongly influence predictions [46]. These techniques enable clinicians to understand and validate AI recommendations, fostering trust and facilitating integration into clinical workflows [47].

Challenges and future directions

Despite promising results, several challenges must be addressed before widespread clinical implementation:

(1) Data quality and standardization: inconsistent data collection practices and lack of standardized definitions for access dysfunction complicate model development and validation [48].
(2) External validation: many AI models have been developed and tested on data from single institutions or specific populations, raising concerns about generalizability to diverse clinical settings [49,50].
(3) Regulatory approval: AI-based clinical decision support tools are subject to evolving regulatory frameworks that vary by jurisdiction, creating barriers to implementation [51].

(4) Integration with existing workflows: successful implementation requires seamless integration with EHRs and dialysis information systems, as well as training for clinical staff [52].

Future research should focus on developing models that are robust across diverse populations and healthcare settings, incorporating federated learning approaches that enable training on distributed datasets while preserving patient privacy [53–56], and conducting prospective clinical trials to demonstrate that AI-enhanced surveillance improves patient outcomes compared to standard care.

Task-shifting models for vascular access management

The global shortage of vascular surgeons and other specialists capable of creating and maintaining hemodialysis access necessitates innovative workforce solutions. Task-shifting, defined by the WHO as the rational redistribution of tasks among health workforce teams, has emerged as a viable strategy to expand access to essential health services, particularly in resource-limited settings [57]. In the context of vascular access, task-shifting involves training nonspecialist practitioners, including nephrologists, general surgeons, and advanced practice nurses, to perform procedures traditionally managed by vascular surgeons or interventional radiologists.

Nephrologist-performed procedures

Nephrologists are uniquely positioned to expand their role in vascular access management due to their longitudinal relationship with ESKD patients and deep understanding of dialysis physiology. Several models of nephrologist-led access creation and maintenance have been successfully implemented globally:

(1) Tunneled catheter insertion: with appropriate training in ultrasound guidance, nephrologists can safely and effectively place tunneled dialysis catheters, reducing reliance on interventional radiology and minimizing procedure delays. Studies from India, Brazil, and parts of sub-Saharan Africa have demonstrated technical success rates of 95–98% with complication rates comparable to those of specialist-placed catheters [14,58].

(2) Endovascular procedures: in a more advanced model, interventional nephrologists perform endovascular procedures, such as angioplasty and thrombectomy to treat access stenosis and thrombosis. This requires dedicated fellowship training (typically 6–12 months) and has been established in countries like the United States, Brazil, and India. Interventional nephrology programs have shown equivalent technical success and patency rates compared to interventional radiology, with the added benefits of reduced procedure delays and potential cost savings of $1500–$2000 per patient annually [59,60].

(3) Surgical AVF creation: while less common, some programs have trained nephrologists in the surgical creation of AVFs, particularly in regions with extreme shortages of surgeons. This model requires intensive, structured training and ongoing mentorship but has proven effective in expanding access to AVF creation in underserved areas [61].

Nurse-led and coordinator models

Task-shifting is not limited to physicians. Specialized nurses and dedicated vascular access coordinators play a crucial role in optimizing access care:

(1) Nurse-led surveillance: advanced practice nurses or specialized dialysis nurses can be trained to conduct systematic access monitoring using physical examination and basic tools. This approach has been shown to enable earlier detection of dysfunction, leading to a 30–40% reduction in thrombosis rates and improved cannulation success [62].

(2) Vascular Access Coordinator Model: this model, implemented successfully in Australia, Canada, and the UK, involves a dedicated coordinator (typically a nurse) who manages the entire access pathway – from planning and creation to monitoring and intervention referral. This coordinated approach has been associated with improved AVF rates, reduced catheter days, and better integration across specialties [63].

Telemedicine and remote guidance

Telemedicine offers a powerful tool for task-shifting, enabling remote specialists to support and mentor local providers. In vascular access, this can involve:

(1) Remote consultation: specialists can remotely review ultrasound images or patient data to guide local providers in access planning and management.

(2) Procedural guidance: real-time video conferencing can be used to guide less experienced practitioners through procedures like catheter insertion or AVF creation.

Telemedicine-supported models have been successfully implemented in rural India, Africa, and Latin America, expanding access to specialist expertise and improving outcomes in remote settings [64].

As the global burden of ESKD continues to grow, task-shifting models represent an essential strategy for addressing vascular access needs. When implemented with appropriate training, quality assurance, and collaborative frameworks, these models demonstrate the potential to expand access to essential procedures while maintaining or improving outcomes for hemodialysis patients worldwide.

Training models and credentialing pathways for nephrologists

The expansion of nephrologist roles in vascular access creation and maintenance necessitates structured training pathways and credentialing standards to ensure procedural competence and patient safety. This section examines established and emerging models for training nephrologists in vascular access procedures, credentialing frameworks, and quality assurance mechanisms essential for successful implementation.

Training curricula and methodologies

Training programs for interventional nephrology vary in duration and intensity, but most incorporate a combination of didactic learning, simulation-based training, and supervised clinical experience. Key components include:

(1) Didactic education: comprehensive instruction on vascular anatomy, pathophysiology of access dysfunction, imaging interpretation (ultrasound and angiography), and procedural techniques.
(2) Simulation training: use of high-fidelity simulators and phantoms allows trainees to develop hand-eye coordination and procedural skills in a controlled environment before performing procedures on patients. Simulation has been shown to shorten the learning curve and improve procedural outcomes [65].
(3) Supervised clinical experience: a cornerstone of training is the performance of a minimum number of procedures under the direct supervision of an experienced mentor. The American Society of Diagnostic and Interventional Nephrology recommends a minimum of 100 endovascular procedures for credentialing in interventional nephrology [66]. For tunneled catheter insertion, 25–50 supervised procedures are typically required [58].
(4) Fellowship programs: formal interventional nephrology fellowship programs, typically 6–12 months in duration, provide the most comprehensive training. These programs are well-established in several countries and produce highly skilled practitioners capable of a wide range of access procedures [59].

Credentialing and certification

To ensure patient safety and maintain high standards of care, formal credentialing and certification processes are essential. These processes typically involve:

(1) Procedural competency assessment: evaluation of a trainee's technical skills, cognitive knowledge, and clinical judgment through direct observation, case log review, and written or oral examinations.
(2) Certification: professional societies, such as American Society of Diagnostic and Interventional Nephrology offer certification programs that provide a recognized standard of excellence in interventional nephrology. Certification typically requires completion of a formal training program, a minimum number of procedures, and passing a certification examination [66].
(3) Institutional credentialing: hospitals and dialysis facilities must establish clear credentialing criteria for practitioners performing vascular access procedures, ensuring that only qualified individuals are granted privileges.

Quality assurance and continuous improvement

Once credentialed, practitioners must engage in ongoing quality assurance and continuous professional development to maintain their skills and stay abreast of new technologies and techniques. Key quality assurance mechanisms include:

(1) Peer review: regular review of procedural outcomes and complications by peers helps identify areas for improvement and ensures adherence to best practices.
(2) Outcomes tracking: systematic collection and analysis of data on procedural success rates, complication rates, and access patency are essential for monitoring performance and identifying trends.
(3) Continuing medical education: participation in continuing medical education activities, including conferences, workshops, and online courses, is critical for maintaining and updating knowledge and skills.

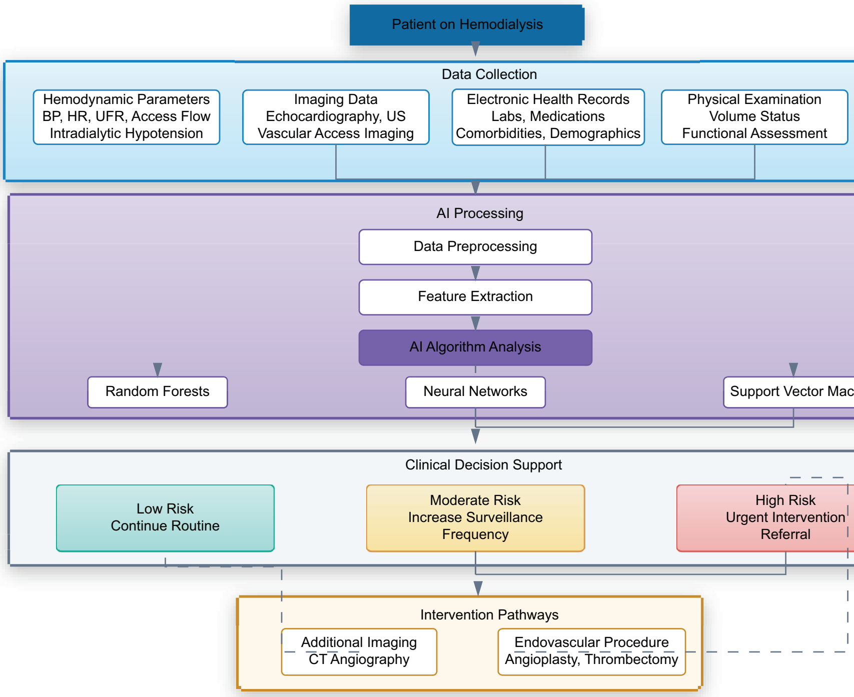
Implementation in resource-limited settings

In resource-limited settings, traditional fellowship programs may not be feasible. Innovative training models are needed to rapidly scale up the workforce. These may include:

(1) Short-course, intensive training: focused, hands-on workshops can be effective for teaching specific procedures like tunneled catheter insertion or basic ultrasound skills.
(2) Tele-mentorship: experienced interventional nephrologists can remotely mentor trainees in underserved areas, providing real-time guidance and support.
(3) Train-the-trainer models: training a cadre of local experts who can then train others in their region is a sustainable approach to capacity building.

By establishing robust training pathways, credentialing standards, and quality assurance mechanisms, the nephrology community can ensure that the expansion of nephrologist roles in vascular access management

Figure 1



AI-enhanced vascular access surveillance workflow. AI, artificial intelligence.

is accomplished safely and effectively, ultimately improving access to high-quality care for hemodialysis patients worldwide.

Implementation challenges and the path forward

Despite the promise of AI-enhanced surveillance and innovative workforce models, significant challenges must be addressed to translate these advances into widespread clinical practice, particularly in resource-limited settings. This final section outlines these barriers and proposes an integrated framework for a path forward (Fig. 1).

Technological and infrastructural barriers

(1) Digital infrastructure: the foundation of AI-driven healthcare is robust digital infrastructure, including reliable internet connectivity, secure data storage, and interoperable EHRs. Many LMICs lack this foundational infrastructure, hindering the collection and analysis of data required for AI models [67].
(2) Equipment costs and maintenance: the capital cost of advanced surveillance equipment (e.g. ultrasound machines, AI software) can be prohibitive. Furthermore, a lack of local technical support for maintenance and repair can render expensive equipment unusable [37].
(3) Data quality and standardization: AI models are only as good as the data they are trained on. Inconsistent data entry, lack of standardized terminology, and incomplete records can compromise the accuracy and generalizability of predictive algorithms [48].

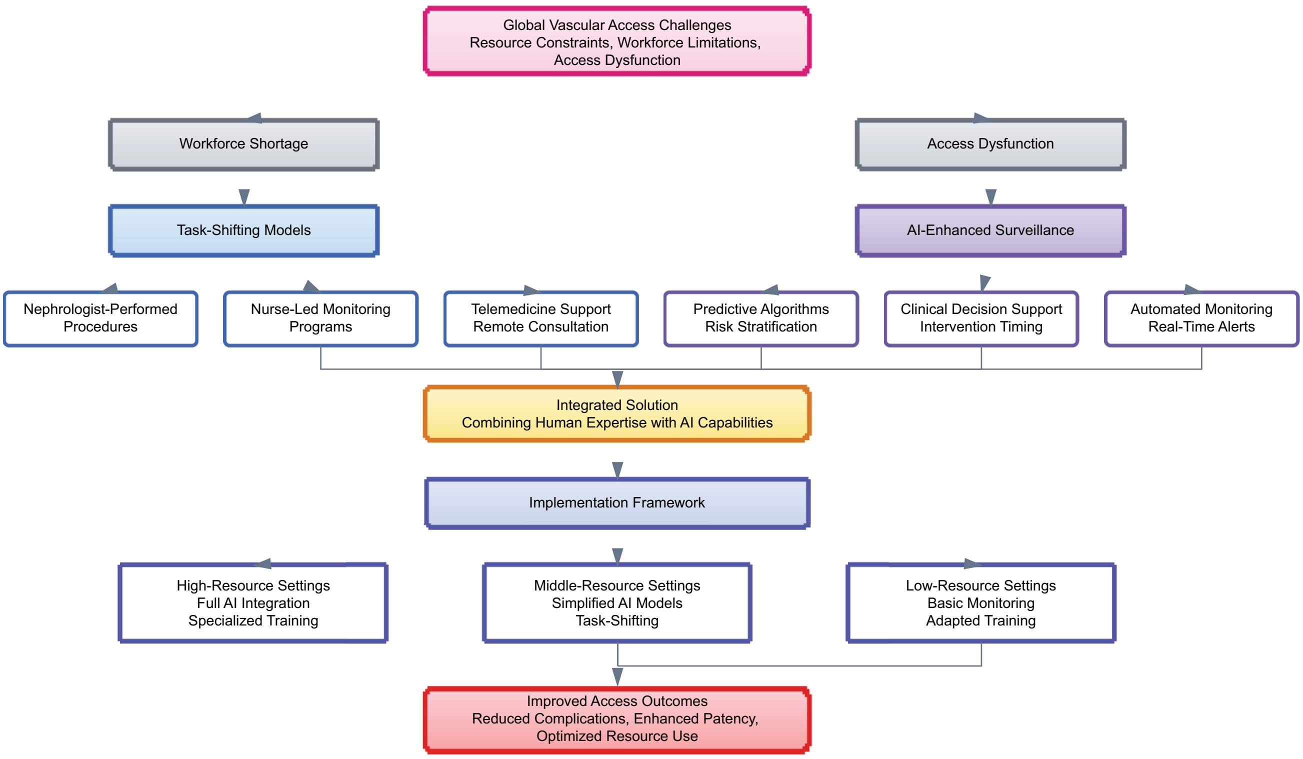
Workforce and training challenges

(1) Shortage of trained personnel: beyond the scarcity of specialists, there is a broader shortage of healthcare workers with the digital literacy and data science skills required to implement and manage AI-based systems.
(2) Training capacity: limited availability of trainers familiar with both the clinical aspects of vascular access and the technical aspects of AI creates a bottleneck in knowledge transfer.
(3) Resistance to change: overcoming established practices and fostering acceptance of new technologies and task-shifting models among healthcare professionals can be a significant challenge.

Regulatory and ethical considerations

(1) Algorithmic bias: AI models trained on data from specific populations may not perform accurately in others, potentially exacerbating existing health disparities. It is crucial to validate algorithms in diverse populations before widespread implementation [68,69].
(2) Data privacy and security: the use of patient data for AI development and surveillance raises significant privacy and security concerns that must be addressed through robust governance frameworks and regulatory oversight [70].

Figure 2



Integrated framework for addressing global vascular access challenges.

Table 1 Global distribution of vascular access types and associated factors

Region	AVF prevalence (%)	AVG prevalence (%)	CVC prevalence (%)	Surgeons per million population	Median wait time for AVF creation
North America	60–65	15–20	15–25	7.2	4–8 weeks
Western Europe	70–80	5–10	10–20	6.8	3–6 weeks
Japan	90–95	1–2	3–8	5.9	2–4 weeks
Australia/New Zealand	75–85	5–10	10–15	6.5	3–6 weeks
Latin America	40–60	5–15	30–50	2.3	8–16 weeks
Middle East/North Africa	50–70	5–10	25–40	3.1	6–12 weeks
Sub-Saharan Africa	20–35	1–5	60–80	0.3	12–24 weeks
South Asia	30–50	5–10	40–65	0.8	10–20 weeks
Southeast Asia	45–65	5–15	25–45	1.2	8–16 weeks
China	60–70	5–10	20–30	2.7	6–12 weeks

AVF, arteriovenous fistula; AVG, arteriovenous graft; CVC, central venous catheter. Data compiled from multiple sources including Dialysis Outcomes and Practice Patterns Study (DOPPS), International Society of Nephrology Global Kidney Health Atlas, and WHO workforce statistics (2020–2025) [15–19].

(3) Accountability and liability: clear guidelines are needed to define accountability when an AI system makes an error or contributes to an adverse patient outcome.

An integrated framework for the future

Addressing these multifaceted challenges requires a coordinated, multistakeholder approach. We propose an integrated framework (Fig. 2) that combines top–down and bottom–up strategies (Tables 1–3):

(1) Global and national leadership: international societies (e.g. ISN, Kidney Disease Improving Global Outcomes) and national governments must collaborate to develop policies that support infrastructure development, establish training standards, and create enabling regulatory environments.

(2) Regional centers of excellence: establishing regional centers of excellence can serve as hubs for training, research, and technical support, fostering local expertise and innovation.

(3) Public–private partnerships: collaboration between academic institutions, healthcare providers, and technology companies can accelerate the development and implementation of affordable, context-appropriate AI solutions.

(4) Phased implementation: a phased approach to implementation, starting with basic surveillance

Table 2 Comparison of artificial intelligence algorithms for vascular access surveillance

Algorithm type	Key features	Sensitivity (%)	Specificity (%)	Data requirements	Implementation complexity	Key studies
Random Forests	Ensemble of decision trees; handles mixed data types; resistant to overfitting	75–85	70–80	Moderate	Low	[10,12]
Support Vector Machines	Optimal boundary classification; effective with limited training data	80–85	75–85	Low-moderate	Low	[42]
Gradient Boosting	Sequential improvement focusing on misclassifications; high accuracy	82–88	78–86	Moderate	Moderate	[40]
Convolutional Neural Networks	Specialized for image analysis; automated feature extraction	85–95	80–90	High (imaging data)	High	[11,41]
Recurrent Neural Networks/ Long Short-Term Memory	Temporal pattern recognition; captures sequential dependencies	85–92	82–89	High (longitudinal data)	High	[43]
Transformer Models	Attention mechanisms; integrates multimodal data; captures long-range dependencies	88–94	85–92	Very high	Very high	[40]
Unsupervised Clustering	Pattern discovery without labeled outcomes; identifies distinct phenotypes	N/A*	N/A*	Moderate	Moderate	[48]

*Sensitivity and specificity are not applicable to unsupervised clustering methods. Performance for these algorithms is evaluated using cluster validity indices (e.g., silhouette score, Davies-Bouldin index) and clinical correlation rather than binary classification metrics. Sensitivity and specificity not directly applicable to unsupervised methods; performance typically measured by cluster validity indices and clinical correlation. Data compiled from published studies evaluating artificial intelligence algorithms for vascular access surveillance between 2020 and 2025.

Table 3 Task-shifting models for vascular access management in global settings

Model	Description	Key personnel	Required training	Implementation settings	Outcomes	Challenges
Nephrologist-performed catheter insertion	Nephrologists trained to place tunneled dialysis catheters using ultrasound guidance	Nephrologists, nephrology fellows	1–3 month focused training; 25–50 supervised procedures	Widely implemented in India, Brazil, Egypt, Thailand, parts of sub-Saharan Africa	Technical success rates 95–98%; complication rates comparable to IR/ surgeons; reduced waiting times	Regulatory barriers; variable training standards; equipment access
Interventional nephrology programs	Comprehensive programs where nephrologists perform endovascular procedures	Interventional nephrologists with dedicated fellowship training	6–12 month fellowship; 50–100 endovascular procedures	Established in USA, Brazil, China, India; emerging in Middle East and Southeast Asia	Equivalent technical success and patency rates to IR; reduced procedure delays; cost savings of $1500–2000 per patient annually	High initial training investment; equipment costs; potential specialty conflicts
Nurse-led access surveillance	Specialized nurses conduct systematic access monitoring using physical examination and basic tools	Advanced practice nurses, specialized dialysis nurses	2-4 week intensive training; ongoing mentorship	Widely applicable; successfully implemented across resource settings	Earlier detection of dysfunction; 30–40% reduction in thrombosis rates; improved cannulation success	Staff turnover; maintaining expertise; clear referral pathways needed
Vascular access coordinator model	Dedicated coordinator (typically nurse) manages access planning, monitoring, and intervention referrals	Vascular access coordinators, access nurses	1–2 month specialized training; communication and systems knowledge	Implemented in Australia, Canada, UK, Singapore; adaptable to various resource levels	Improved AVF rates; reduced catheter days; better coordination across specialties	Requires system-level support; role definition; integration with existing workflows
Telemedicine-supported access management	Remote specialist consultation supporting local providers in access care assessment and management	Local nephrologists/ nurses with remote specialist support	Basic procedural training plus telemedicine familiarity	Rural settings in India, Africa, Latin America; Island nations	Expanded access to expertise; comparable outcomes to in-person assessment in selected procedure	Connectivity requirements; legal/licensure issues; technology limitations
Simplified bedside procedures	Adapted techniques for catheter insertion and basic interventions without advanced imaging	Nephrologists, advanced practice providers	Focused training on adapted techniques; 15–30 supervised procedures	Emergency settings; resource-limited environments; disaster response	Acceptable technical success (85–90%); higher minor complication rates but similar major complications	Limited to specific procedures; requires careful patient selection; not suitable for complex anatomy

Data compiled from published studies, international nephrology society reports, and implementation case studies (2020–2025) [13,14,54–60]. AVF, arteriovenous fistulas.

techniques and gradually incorporating more advanced technologies as infrastructure and workforce capacity grow, is a pragmatic strategy for resource-limited settings.

(5) Focus on equity: a central tenet of this framework must be a commitment to health equity, ensuring that technological advances and workforce innovations benefit all patient populations, regardless of geographic location or socioeconomic status.

Future directions

Several emerging technologies and approaches hold promise for further advancing vascular access care:

(1) Multimodal AI integration: future systems will likely integrate data from multiple sources (hemodynamic, imaging, acoustic, EHR) to provide comprehensive, real-time assessment of access function [40].

(2) Explainable AI: continued development of interpretable models that provide clinicians with insight into the reasoning behind predictions will facilitate trust and adoption [46,47].

(3) Federated learning: privacy-preserving ML techniques that enable algorithm training across distributed datasets without centralizing sensitive patient information could accelerate model development while addressing privacy concerns [53–56].

(4) Point-of-care devices: development of low-cost, portable devices for access surveillance (e.g. smartphone-based acoustic analysis) could democratize access to advanced monitoring technologies [11].

(5) Precision medicine approaches: AI models that incorporate genetic, proteomic, and other biomarker data may enable personalized prediction of access outcomes and guide individualized management strategies [71].

Conclusion

The dual challenges of vascular access dysfunction and workforce shortages represent a critical threat to the well-being of the global hemodialysis population. The convergence of AI-powered surveillance and innovative task-shifting models offers a transformative opportunity to address these challenges. AI algorithms can provide early, accurate prediction of access failure, enabling timely intervention and prolonging access survival. Simultaneously, empowering nephrologists and other healthcare professionals to take on expanded roles in access management can overcome the critical shortage of specialists.

Realizing this potential, however, requires a concerted effort to address the significant implementation barriers that exist. By adopting an integrated, equity-focused framework that combines technological innovation with workforce development and supportive policy, the global nephrology community can pave the way for a future where every hemodialysis patient has access to a safe and reliable lifeline. The path forward demands collaboration across disciplines, sectors, and borders, united by a shared commitment to improving outcomes for the millions of individuals worldwide who depend on hemodialysis for survival.

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