International Journal of Multiphysics
Volume 18, No. 3, 2024
ISSN: 1750-9548

Inflammatory Biomarkers in Arteriovenous Fistula Maturation Failure: A systematic Review

Reem Nasser Abdel-Aal*, Khaled Mohamed Talaat, George Emad Shaker, Fatma Mohammed Attia

Internal Medicine Department, Faculty of Medicine, Zagazig University

***Corresponding author:** Reem Nasser Abdel-Aal

Abstract

Arteriovenous fistula (AVF) is the preferred vascular access for maintenance hemodialysis in patients with end-stage renal disease. However, maturation failure remains a frequent and costly clinical challenge, adversely affecting dialysis adequacy, patient outcomes, and healthcare expenditure. Accumulating evidence indicates that systemic inflammatory biomarkers, including the neutrophil-to-lymphocyte ratio (NLR), platelet-to-lymphocyte ratio (PLR), systemic immune-inflammation index (SII), prognostic nutritional index (PNI), and calcium-phosphorus product, may function as accessible and cost-effective tools for predicting AVF maturation failure. This review examines the current literature on the role of these inflammatory and nutritional indices in forecasting AVF dysfunction, examines associated clinical and demographic risk factors, and discusses the practical implications for preoperative risk stratification in hemodialysis populations.

Keywords: arteriovenous fistula; maturation failure; inflammatory biomarkers; neutrophil-to-lymphocyte ratio; platelet-to-lymphocyte ratio; systemic immune-inflammation index; prognostic nutritional index; hemodialysis; vascular access

Introduction

Chronic kidney disease is a growing global health concern, with the worldwide prevalence of kidney failure estimated at approximately 5.3 million individuals as of 2017, and millions more lacking access to any form of kidney replacement therapy. The Kidney Disease Improving Global Outcomes guidelines classify CKD into five stages based on estimated glomerular filtration rate, with the fifth stage further subdivided according to dialysis dependence. Among available renal replacement modalities, hemodialysis is the most widely used, sustaining the lives of approximately 1.5 million patients with end-stage renal disease worldwide. The procedure functions by artificially removing excess fluid, minerals, and metabolic waste products from the blood, though it carries inherent cardiovascular risks and is associated with notable morbidity and mortality [1].

Reliable vascular access is a prerequisite for effective hemodialysis, and the quality of that access directly influences dialysis adequacy and patient survival. Among the available options, the autologous arteriovenous fistula is widely endorsed as the preferred form of vascular access because of its association with lower infection rates, fewer interventions, and improved long-term survival compared to arteriovenous grafts and central venous catheters. The National Kidney Foundation guidelines recommend native AVFs, which achieve primary success in approximately 65% of patients initiating hemodialysis [2].

Despite these advantages, AVF maturation failure remains a persistent and costly clinical problem. The Kidney Disease Outcomes Quality Initiative "Rule of 6s" defines a mature fistula as one that, six weeks after creation, achieves a blood flow rate of at least 600 mL/min, a diameter of at least 6 mm, a cannulation length of 6 cm, and a depth no greater than 6 mm from the skin surface. Failure to meet these criteria is associated with increased morbidity, additional surgical interventions, prolonged catheter dependence, and elevated healthcare expenditures [3].

A growing body of evidence points to systemic inflammation as a central mechanism in AVF dysfunction, promoting neointimal hyperplasia, venous stenosis, and a procoagulant state. In parallel, nutritional and immunological derangements commonly observed in ESRD patients may further compound this process [4].

Hemodialysis

Principles, Indications, and Complications

Hemodialysis is a life-sustaining therapy that replaces the excretory and regulatory functions of the failed kidneys by removing metabolic waste products and excess fluid while helping maintain electrolyte balance and blood pressure. Initiation of maintenance dialysis should be guided by clinical indications, including uremic symptoms, refractory metabolic or electrolyte disturbances, uncontrolled volume overload, declining nutritional status despite intervention, or cognitive impairment, rather than by estimated kidney function alone in asymptomatic patients [5].

Intradialytic hypotension is the most frequently encountered adverse event during hemodialysis and can lead to poor long-term outcomes, including higher mortality and myocardial stunning. A systolic blood pressure falling below 90 mmHg strongly predicts risk, and management includes placing the patient in the Trendelenburg position, giving a rapid saline bolus, reducing ultrafiltration rate, and monitoring until vital signs stabilize [6].

Cardiovascular disease is the leading cause of death in dialysis patients, with inflammation, oxidative stress, and endothelial dysfunction playing contributory roles. During dialysis, contact between blood and the dialyzer membrane triggers immune activation and the release of reactive oxygen species, amplifying oxidative damage. Patients with nonfunctioning kidneys also generate free radicals from activated macrophages and vascular cells, which exacerbate multi-organ injury [7].

Malnutrition is another significant concern, affecting an estimated 43% of dialysis patients worldwide, driven by dialysis-induced nutrient losses, inadequate dietary protein intake, taste alterations, poor appetite, insulin resistance, and psychosocial factors. Each dialysis session can remove approximately 6 to 12 grams of amino acids and 7 to 8 grams of protein, which, when combined with insufficient dietary protein intake, increases malnutrition risk. Early nutritional assessment and timely interventions are essential to improve patient outcomes [8].

The malnutrition-inflammation-atherosclerosis syndrome, frequently observed in hemodialysis patients, contributes to accelerated cardiovascular disease, sarcopenia, and increased mortality. It is associated with persistent inflammation, decreased protein synthesis, and low albumin levels. Comorbidities like heart failure and chronic kidney disease-bone mineral disorder have a bidirectional relationship with nutritional status through mechanisms including malabsorption, reduced appetite due to cytokines, and challenges in oral intake from fatigue or dyspnea [9].

Taste alterations affect 31 to 44% of hemodialysis patients, often leading to aversions to protein-rich foods like meat, and these taste changes, possibly linked to zinc deficiency, reduce appetite and diet quality through learned food aversions, contributing to malnutrition. Poor appetite among HD patients is associated with significantly higher hospital admission frequency, longer hospitalization, and worse nutritional and inflammatory outcomes [10].

The malnutrition inflammation score (MIS) has been introduced as a quantitative tool that encompasses seven original subjective global assessment components plus body mass index, serum albumin, and total iron-binding capacity, providing a composite measure ranging from 0 (normal) to 30 (severely abnormal). A higher score reflects a more severe degree of malnutrition and inflammation, and it has become a validated instrument frequently used for assessing nutritional and inflammatory status in dialysis patients [11].

Dialysis disequilibrium syndrome is another recognized complication, with patients undergoing rapid dialysis developing seizures and cerebral edema more frequently. A reasonable goal of urea concentration reduction is

40% over two hours, and adding osmotic agents such as sodium, mannitol, high glucose dialysate, or glycerol to the blood can prevent the osmotic gradient from forming. Setting the dialysate sodium concentration higher throughout the treatment may also be beneficial [12].

Vascular access dysfunction, most commonly stenosis of the arteriovenous fistula, is a strong determinant of dialysis patient quality of life. Stenosis leads to reduced blood flow and increased risk for thrombosis, underscoring the importance of reliable vascular access creation and maintenance in this population [13].

Arteriovenous Fistula

Creation, Types, and Maturation

An arteriovenous fistula is a surgically created connection between an artery and a vein, typically in the upper extremity, intended to provide reliable vascular access for hemodialysis. The maturation process involves venous arterialization, characterized by nitric oxide-mediated remodeling and elastin degradation, leading to progressive vein dilation and increased blood flow sufficient for dialysis. Clinically mature AVFs are easier to cannulate with repetitive needle sticks and provide high flow rates necessary to sustain hemodialysis [14].

Dialysis fistula planning begins with careful patient selection through history, physical examination, and vascular assessment, including vein inspection, pulse symmetry, blood pressure measurement, and the Allen test. Preoperative duplex ultrasound vein mapping is universally recommended, with KDOQI guidelines specifying a minimum vein diameter of 2.0 to 2.5 mm, a cannulation segment of at least 6 cm, and patent central and draining veins. The Society of Vascular Surgery recommends placing access as distally as possible in the upper extremity to preserve future central access options, with preference for the non-dominant arm [15].

Duplex ultrasound is also used to assess arteriovenous fistula maturation and predict functional efficiency, and a more comprehensive understanding of the determinants of successful fistula development may help improve vascular access outcomes. Creation of an arteriovenous fistula produces increased and turbulent blood flow that elevates shear and hoop stresses, stimulating vascular remodeling characterized by luminal dilation and wall thickening; fistula failure occurs when adaptive dilation is replaced by venous stenosis, leading to increased resistance and reduced blood flow [16].

The radiocephalic fistula, first described by Cimino and Brescia in 1966, remains the first-choice access owing to lower rates of steal syndrome compared with upper arm fistulas and because its creation preserves the future option for a more proximal fistula when the access fails. However, the maturation rate for radiocephalic fistulas is poor, with some studies showing that up to two-thirds fail to mature [17].

A major cause of fistula non-maturation is juxta-anastomotic stenosis (JAS), defined as a more than 50% reduction of the luminal diameter of the outflow vein within 2 to 5 cm from the arteriovenous anastomosis. JAS is the most frequent stenosis seen in radiocephalic fistulas and is more commonly observed in radiocephalic configurations than in any other type of AVF, although hemodynamically significant JAS is present in up to 22% of brachiocephalic fistulas [18].

The brachiocephalic fistula is indicated when a forearm fistula has failed or forearm vessels are unsuitable on preoperative mapping. For brachiocephalic fistula creation, adequate vasculature generally includes an arterial diameter greater than 2 mm and a vein diameter greater than 2.5 mm under tourniquet application. It typically matures faster and has higher patency than radiocephalic fistulas, though its placement precludes the opportunity for subsequent creation of a more distal fistula [19].

There is an estimated 5 to 20 times increased rate of steal syndrome in patients with brachiocephalic fistulas compared to those with radiocephalic fistulas, and when severe, steal syndrome may result in tissue loss. Primary brachiocephalic fistulas are preferred in patients with multiple comorbidities due to higher maturation rates and superior patency. The most frequent cause of dysfunction in a brachiocephalic fistula is cephalic arch stenosis (CAS), seen in 30 to 77% of dysfunctional brachiocephalic fistulas [20].

The brachiobasilic fistula is indicated when radiocephalic or brachiocephalic fistulas are unsuitable or have failed. The basilic vein's deep, medial position protects it from prior punctures but requires elevation and lateral transposition for dialysis access. The one-stage approach may reduce overall cost and shorten time to cannulation, whereas the two-stage approach facilitates easier mobilization of an arterialized basilic vein and allows interval patient selection [21].

Autologous arteriovenous fistulas are the preferred vascular access for hemodialysis; however, patients who are elderly with small-caliber vessels, have poor vasculature with calcification or diabetes, have slowly progressive chronic kidney disease, or have poor health and limited life expectancy are unlikely to benefit from AVF creation. A patient-centered approach must be taken, including patient preferences, attributes, life expectancy, and quality of life when considering vascular dialysis access [22].

Mechanisms and Patterns of AVF Maturation Failure

Maturation failure is broadly defined as the inability to use a fistula for dialysis within three months of its creation and is the most common barrier to establishing permanent vascular access. Effective intervention depends on routine surveillance to identify fistulas at risk of failure, and physical examination during dialysis, including assessment of thrill, collapse on elevation, and pulse augmentation with venous occlusion, remains fundamental to this process [23].

A diminished or absent thrill suggests impending fistula failure, while failure of the fistula to collapse when elevated above heart level indicates impaired outflow, most commonly due to venous stenosis. Prolonged bleeding with cannulation or the aspiration of clots may also be signs of fistula dysfunction, and there is strong agreement between physical examination and angiography regarding the presence of venous stenosis [24].

A well-functioning fistula has blood flow of 700 to 1300 mL/min, and flow less than 500 mL/min or a decrement from baseline flow of 25% or more are signs of impending failure. Vascular access blood flow strongly predicts venous stenosis and thrombosis, and monitoring of fistula access by blood flow measurement has been shown to decrease morbidity and cost in these patients [25].

Juxta-anastomotic stenosis is the most common culprit lesion in non-maturing fistulas, implicated in as many as 64% of cases, and is defined as a greater than 50% reduction in the lumen of the draining vein within the first 4 cm from the arterial anastomosis. Less common causes of non-maturation include arterial stenosis, central venous stenosis, and the presence of collateral veins, all of which reduce inflow or prevent the development of adequate pressures to promote fistula dilation [26].

Cephalic arch stenosis is uncommon in radiocephalic fistulas but is a frequent cause of brachiocephalic fistula dysfunction. In brachiobasilic fistulas, vein transposition creates a sharp angulation that predisposes to stenosis, accounting for approximately two-thirds of cases. All three of these characteristic lesions occur at sites where the venous outflow makes a sharp change in course, exposing the vessel wall to disturbed flow and altered shear stress [27].

Thrombosis within the fistula is the terminal event in the natural history of venous stenosis-driven dysfunction, and a decline in access blood flow is the strongest predictor of impending thrombosis. Early thrombosis, occurring within 30 days of creation, has historically been attributed to technical factors, while later events are more strongly associated with progressive stenosis, elevated hematocrits from erythropoiesis-stimulating agents, diabetes, female sex, and thrombophilia [28].

Anastomotic stenosis due to neointimal hyperplasia is a leading cause of AVF non-maturation and is defined as a greater than 50% reduction in the luminal diameter of the outflow vein. Advanced age and reduced vascular compliance, along with comorbidities such as hypertension, diabetes, obesity, heart failure, and peripheral atherosclerosis, increase the risk of maturation failure. Preoperative vascular mapping increases the likelihood of successful AVF maturation, with minimum recommended diameters of 2.5 mm or greater for veins and 2 mm or greater for arterial inflow [29].

Complications of Arteriovenous Fistulas

As with any surgical procedure, there is a risk of bleeding, infection, or damage to surrounding structures during AVF creation. Complications can be divided into immediate (hematoma, bleeding, edema, ischemic steal syndrome, or loss of thrill secondary to acute thrombosis), early (stricture, thrombosis, infection, venous hypertension, central venous stenosis, or failure to mature), and late (aneurysm, stricture, late thrombosis, infection, or neuropathy) [30].

Repeated needle cannulation at a single site weakens the access wall and promotes aneurysm formation, and progressive aneurysmal dilation may result from chronically high flow and elevated intra-access pressures. Surgical intervention is generally indicated when there is skin compromise, ulceration, or loss of safe cannulation sites, as untreated high-risk aneurysms may rupture and cause life-threatening hemorrhage [31].

Most AVF infections present as perivascular cellulitis with erythema, edema, and sometimes systemic features. Localized infections can usually be managed with targeted antibiotic therapy guided by wound and blood cultures, whereas more severe infections involving aneurysm, hematoma, or abscess typically require surgical excision and drainage [31].

Thrombosis is the most common fistula complication and occurs in areas of stenosis, either at the anastomosis or fistula vein, with the risk of thrombosis increasing with the degree of stenosis. Ischemic steal syndrome results from reduced distal limb perfusion after AVF creation and may cause pain, sensory or motor deficits, and neuropathy, occurring less frequently in forearm fistulas than in upper arm fistulas [31].

Venous hypertension is most often caused by central venous stenosis, usually due to prior central venous catheter or device placement. It leads to elevated venous pressures transmitted to the fistula and upper limb, causing arm swelling, pain, cannulation difficulties, increased venous pressures during dialysis, and reduced dialysis efficiency [31].

Inflammatory Biomarkers and Their Role in Predicting AVF Failure

Systemic inflammation is a hallmark of advanced CKD and plays a central role in vascular remodeling, endothelial dysfunction, and thrombogenesis at dialysis access sites. Inflammatory markers typically refer to laboratory tests that measure specific acute phase proteins, also known as acute phase reactants, though this term can encompass any marker of inflammation, including the white blood cell count [32].

Exploring the role of inflammatory markers such as the neutrophil-to-lymphocyte ratio and platelet-to-lymphocyte ratio could reveal the subclinical systemic inflammatory status that could lead to premature AVF failure. After a detailed analysis of the literature, the most promising biomarkers are serum albumin, NLR, C-reactive protein, mean platelet volume, PLR, SII, interleukin-6, red cell distribution width, and fibrinogen [33].

The neutrophil-to-lymphocyte ratio, calculated as the total neutrophil count divided by the total lymphocyte count, was first proposed as a biomarker of systemic inflammation and immune activation more than two decades ago. It has since been validated across multiple clinical settings, including cardiovascular pathologies and surgical outcomes, and its simplicity and low cost make it particularly attractive for routine clinical application [34].

Yilmaz and colleagues in 2014 identified that elevated baseline NLR values were positively associated with the presence of AVF stenosis, with an optimal cutoff value of 2.7 yielding a sensitivity of 98.4% and a specificity of 75%. This landmark study established NLR as a potential screening tool for vascular access dysfunction in chronic hemodialysis patients [35].

Usman and colleagues validated these results on a cohort of 300 patients, in which they followed AVF dysfunction three months postoperatively. The authors identified an optimal cutoff value of NLR of 2.65 with a sensitivity of 98% and a specificity of 80%, confirming the predictive utility of this biomarker across different populations [36].

Wongmahisorn and colleagues identified a similar cutoff value of 2.7, above which they demonstrated a five-fold higher risk of AVF failure at three months. Furthermore, Kaller and colleagues and Pasqui and colleagues showed that high NLR values are associated with maturation failure at six to eight weeks and with long-term patency loss, with a positive correlation between NLR, PLR, SII, interleukin-6, and the extent of intimal hyperplasia in venous wall specimens [37].

Bashar and colleagues revealed that overall AVF functional maturation rate in their study was 53.7%, and patients with matured AVFs had a significantly higher NLR compared with the non-matured group, confirming that increased levels of NLR were associated with fistula maturation outcomes [38].

The platelet-to-lymphocyte ratio, calculated as the total platelet count divided by the total lymphocyte count, is another easily obtainable parameter that reflects systemic inflammation and has been linked to chronic inflammatory conditions across multiple clinical settings. It was first proposed as an accessible and reliable marker to predict prognosis in oncological patients and has since been investigated in vascular access outcomes [39].

Sarioglu and colleagues revealed through logistic regression analysis that PLR did not independently predict AVF thrombosis and stenosis; nevertheless, they suggested that high levels of PLR may be a supportive finding of AVF stenosis and thrombosis and may be taken into consideration during the follow-up of hemodialysis-dependent patients [40].

In 2024, Franchin and colleagues evaluated the predictive value of NLR, PLR, and SII in the onset of arteriovenous graft stenosis. The authors highlighted how higher values of NLR and SII were related to stenosis onset and recurrence; contrariwise, they did not find statistical differences between AVG stenosis and PLR values, suggesting that the role of PLR may be more limited compared to other inflammatory indices [41].

The systemic immune-inflammation index, calculated as the product of neutrophil and platelet counts divided by the lymphocyte count, integrates three cellular components and was originally developed for prognostic assessment in hepatocellular carcinoma. It has since gained attention as a predictor of adverse outcomes across multiple disease settings, including cardiovascular conditions and oncological pathologies [42].

Song Ren and colleagues in 2024 included 2690 patients and found that among several systemic immune-inflammation indices, SII exhibited the strongest prognostic value for hemodialysis access failure, with NLR and PLR values of 5.35 and 191.28 for the failed AVF group, respectively. These findings strongly support the predictive value of composite inflammatory indices in identifying patients at high risk for vascular access failure [43].

Prognostic Nutritional Index and Albumin

Nutritional and immunological assessments provide complementary information about the systemic status of ESRD patients and their capacity for successful vascular remodeling. The prognostic nutritional index, developed by Onodera and colleagues in 1984, is derived from serum albumin levels and total lymphocyte count using the formula: PNI = serum albumin (g/L) + 5 × lymphocyte count (10^9/L), and was originally designed to evaluate the nutritional and immunological status of surgical oncology patients [44].

In a large study of more than 100,000 hemodialysis patients, PNI showed superior predictive performance for mortality compared to serum albumin or lymphocyte count alone, and it has emerged as a simple and practical predictor in patients undergoing hemodialysis. Its effectiveness in evaluating nutritional status and predicting outcomes in HD patients undergoing surgery is a pertinent clinical question [45].

Kaller and colleagues highlighted the protective role of higher PNI values against thrombosis and AVF maturation failure, with levels below 39 indicative of elevated risk. Their findings indicated that higher preoperative PNI values can effectively predict AVF maturation failure, early thrombosis, and short-term mortality, establishing PNI as a meaningful preoperative biomarker [33].

Kurumisawa and colleagues demonstrated that a PNI of 34 or less served as a robust independent predictive factor for long-term mortality in hemodialysis patients undergoing cardiac surgery. Barutcu Atas and colleagues similarly found that a baseline PNI value below 39 was correlated with mortality in a retrospective study of 359 patients over the age of 80 with CKD stage 3 to 4 [46].

Wada and colleagues established the involvement of PNI in the development of significant adverse cardiac events in a group of 1988 patients with stable coronary arteries, further broadening the clinical applicability of this nutritional index beyond nephrology and surgical settings [47].

Hypoalbuminemia, aside from being a marker of dietary deficiency in uremic patients, also reflects underlying inflammation, and its association with AVF obstruction has been documented in multiple studies. Churchill and colleagues found that arteriovenous graft obstruction was most frequently determined by hypoalbuminemia, and further investigations have revealed that hypoalbuminemia is also a symptom of systemic inflammation, with the indirect conclusion that inflammation is involved in AVF thrombosis [48].

On the contrary, in a study by Song Ren and colleagues, PNI was not the main predictive inflammatory biomarker, with a cutoff value of almost 41.6 for both survival and failed groups, in comparison with the SII. This suggests that while PNI carries prognostic value, its predictive strength may vary depending on the population and the competing inflammatory indices being evaluated [43].

Calcium-Phosphorus Product and Vascular Calcification

Hyperphosphatemia is the most common metabolic complication in maintenance hemodialysis patients, and elevated extracellular inorganic phosphate stimulates the synthetic transformation of vascular smooth muscle cells, induces apoptosis pathways, and triggers progressive vascular calcification. This calcification accelerates vessel injury and thrombosis, ultimately contributing to AVF failure [49].

The 2003 K/DOQI guidelines recommend maintaining the calcium-phosphorus product below 55 mg^2/dL^2 in patients with CKD stage 5 and those on dialysis. However, some investigators have argued that this threshold may be oversimplified, as actual calcium-hydrogen phosphate precipitation in plasma may require a product level three times higher than the KDOQI cutoff [50].

Kaller and colleagues reported significantly elevated calcium-phosphorus product values in the AVF dysfunction group compared to those with functioning fistulas. Tüysüz and colleagues found that patients with a calcium-phosphorus product of 50 mg^2/dL^2 or greater had significantly higher rates of redo surgery, further supporting the role of mineral metabolism derangements in access failure [51].

In contrast, Long and colleagues observed that calcium-phosphorus product did not emerge as an independent predictor of late AVF failure in their cohort over a 36-month follow-up, with almost the same values in both patent and failed groups. This suggests that the predictive value of this marker may vary depending on the timing and chronicity of the outcome assessed [52].

Elevated calcium-phosphorus product promotes medial vascular calcification, reducing vessel compliance and impairing adaptive outward remodeling, which is an essential requirement for AVF maturation. Calcified veins are also more prone to endothelial injury and early thrombosis, supporting the recommendation to maintain the calcium-phosphorus product at optimal levels in these patients to avoid both the risk of AVF re-operation and other cardiovascular complications [53].

Hemoglobin, Anemia, and Erythropoietin Administration

Anemia is a near-universal finding in patients with advanced CKD and is driven by reduced erythropoietin production, iron deficiency, chronic inflammation, and shortened red blood cell survival. Although erythropoietin and iron therapy improve hemoglobin levels and relieve symptoms, raising hemoglobin above certain thresholds does not improve CKD prognosis and may increase the risk of cardiovascular events and AVF thrombosis through elevated blood viscosity [54].

Ge and colleagues indicated that the average hemoglobin level in the AVF failure group was higher than in the patency group, suggesting that hemoglobin increases may contribute to fistula obstruction. The relationship between hemoglobin and AVF outcomes appears to be nonlinear: hemoglobin serves as a protective factor when evaluated as a continuous variable, with each g/dL decrease in hemoglobin associated with approximately a 30% increase in risk, but levels above 13.0 g/dL begin to function as a risk factor for vascular access failure [55].

It is also reported that certain materials can lead to eosinophil increase during dialysis, such as ethylene oxide and heparin. Studies have indicated that there is a recognized clinical link between hypereosinophilic syndrome and thrombosis, and that eosinophil cationic protein can enhance factor oxidation dependence and lose the anticoagulant activity of heparin [55].

Regarding erythropoietin administration, previous studies indicated that patients with AVF problems had received increased doses of erythropoiesis-stimulating agents. Hemodialysis activates coagulation through blood-membrane contact, generating procoagulant mediators that return to the AV fistula and promote local thrombosis, and this effect appears both local and systemic [56].

Erythropoietin receptors are present on vascular smooth muscle cells, and EPO stimulates their dose-dependent proliferation, promoting vascular remodeling and stenosis. Stenotic AVF lesions show increased expression of EPO receptors and transforming growth factor-beta, implying that exogenous EPO may promote smooth muscle proliferation and extracellular matrix deposition. Compared with intravenous dosing, subcutaneous EPO produces lower but sustained plasma levels and has been associated with higher vascular access failure, possibly due to prolonged receptor activation [57].

EPO has also been shown to stimulate production of plasminogen activator inhibitor-1, promote vascular smooth muscle cell proliferation, increase platelet production, and enhance platelet activity. These events can contribute to vascular access stenosis and occlusion by promoting intimal hyperplasia and thrombosis, and their effects may be amplified with long-acting EPO agents [58].

Risk Factors for AVF Failure

Elderly patients, who have higher rates of diabetes and peripheral vascular disease, show increased primary failure and reduced patency of radiocephalic AVFs. Elderly patients experience poorer AVF outcomes than younger individuals, with increased radial artery intima-media thickness associated with older age predicting early AVF failure, likely due to reduced vascular elasticity and increased arterial stiffness [59].

However, some studies did not support worse AVF patency rates in older patients. Qiong T and colleagues showed that age was not significantly different between the failure group and the non-failure group, suggesting that the construction of AVFs should not be affected by age alone and that other biological factors may be more determinant [60].

Although women have traditionally been thought to have smaller vessels, emerging evidence challenges this assumption. A large retrospective study assessing vessel diameters across multiple arterial and venous sites found no significant sex-based differences in vascular size, and a meta-analysis similarly demonstrated comparable one-year patency and maturation rates for radiocephalic AVFs in men and women [61].

Female sex, recognized as an independent risk factor for AVF failure, is further compounded by altered platelet function and increased neointimal hyperplasia. Experimental evidence suggests that reduced estrogen levels attenuate vascular protective mechanisms, while testosterone deficiency promotes venous wall thickening. Estrogen maintains vascular homeostasis by enhancing nitric oxide production and inhibiting inflammatory adhesion molecules, and its deficiency in postmenopausal women may exacerbate inflammatory responses, contributing to higher AVF failure rates [62].

Diabetes mellitus is a well-established contributor to poor AVF outcomes through its association with endothelial dysfunction, arterial calcification, and a proinflammatory vascular milieu, all of which impair outward

remodeling. The changes in metabolism that accompany diabetes can manifest as pro-thrombotic situations, endothelial damage, deregulated growth factors, and increased extracellular matrix deposition [63].

Bin Zhao and colleagues discovered that type 2 diabetes significantly increased the risk of AVF non-maturation, mediated primarily by changes in cephalic vein diameter. Another systematic review reported that early AVF failure was significantly associated with a distal fistula location, small arterial diameter, small vein diameter, low serum albumin, female gender, and diabetes mellitus [64].

Hypertension impairs endothelial function, reducing vascular relaxation and promoting inflammatory cell infiltration, eventually infiltrating the smooth muscle layer, depositing connective tissue, and promoting neovascularization. However, a recent study by Zhao and colleagues did not find any positive correlation between hypertension and AVF maturation, indicating that the direct contribution of hypertension remains debatable [65].

Peripheral vascular disease is four times more prevalent in people with diabetes than in those without and develops gradually due to systemic atherosclerosis. A retrospective longitudinal cohort study found that an ankle-brachial pressure index below 0.9, a reliable marker of peripheral vascular disease, was significantly associated with vascular access failure after adjustment for confounders [66].

Smoking contributes to greater thrombosis risk and poorer primary and secondary patency through its effects on endothelial dysfunction, accelerated atherosclerosis, and oxidized lipid metabolism. In addition, progression of atherosclerosis and ischemic nephropathy may contribute to vascular complications in CKD [67].

Obesity continues to impact public health and is considered a growing global health challenge, with increasing class of obesity associated with increased comorbidity burden and lower life expectancy. Interleukin-6 stimulates the production of C-reactive protein, and high levels of C-reactive protein have been recorded in obese patients, with evidence that C-reactive protein contributes to advancement of myointimal hyperplasia, providing further evidence of the high rate of AVF failure in obese patients [68].

Late referral of patients initiating dialysis therapy with a temporary central venous catheter can impair patency rate and fistula maturation. This can lead to the development of complications such as insufficient blood flow, hematoma formation, recurrent thrombosis, fibrosis, vessel wall damage, and bacteremia. The vascular access guidelines issued by KDOQI introduced the concept of "Fistula First" to address this concern [69].

Coagulation Factors and Lipid Profile

Arteriovenous fistula dysfunction is a major source of morbidity and mortality in hemodialysis patients, most commonly due to failure of new fistulas to mature or stenosis in established accesses, with venous stenosis particularly in the juxta-anastomotic swing segment accounting for a substantial proportion of mature AVF failures. The vascular endothelium maintains antithrombotic and anticoagulant balance, and endothelial injury promotes platelet adhesion and coagulation, potentially leading to vascular obstruction [70].

In a multicenter, double-blind, placebo-controlled trial of 877 patients undergoing AVF surgery, clopidogrel significantly reduced early fistula thrombosis compared with placebo. A systematic review of randomized controlled trials evaluating antithrombotic or antiplatelet therapies found that antiplatelet drugs can reduce early AVF and graft thrombosis, supporting their feasibility in ESRD patients, though long-term efficacy and safety remain uncertain [71].

The relationship between serum lipid profiles and AVF maturation remains unclear. Patients with thrombosed fistulas had lower HDL and albumin, higher LDL, and elevated C-reactive protein, suggesting that dyslipidemia and systemic inflammation may influence AVF outcomes. Classic uremic dyslipidemia is characterized by elevated triglycerides, reduced HDL, and low total cholesterol, exacerbated by advanced kidney failure [72].

In a single-center case-control study of 60 patients with autologous AVFs, use of folic acid and statins was associated with improved two-year fistula patency compared with no statin therapy. In CKD, accelerated atherosclerosis leads to heavily calcified, subintimal plaques, and elevated lipid levels also disrupt key vascular

mediators including angiotensin II, endothelin-1, and nitric oxide, potentially impairing renal and vascular function [73].

Vessel Diameter, Cannulation Technique, and Additional Considerations

Preoperative vessel diameter is one of the strongest predictors of AVF maturation success. The European Society of Vascular Surgery advocates minimum diameters of at least 2 mm for both artery and vein when planning radiocephalic fistulas, though evidence suggests that larger calibers yield more favorable outcomes. Vein diameter, in particular, appears to be a more robust independent predictor of long-term patency than arterial diameter, even after adjustment for cardiovascular risk factors [74].

Kaller and colleagues identified threshold values of 2.25 mm for radial artery and 2.55 mm for cephalic vein regarding maturation failure, and observed that intimal hyperplasia and angiogenesis are associated with radiocephalic AVF maturation failure. Hou and colleagues observed in multivariate analysis that a cephalic vein diameter exceeding 2 mm predicted successful radiocephalic AVF development [75].

Li and colleagues, in a large cohort of 277 Asian patients, determined optimal cutoff diameters of 1.85 mm for cephalic vein and 2.05 mm for radial artery. These findings underscore the importance of preoperative vessel assessment in predicting AVF outcomes and support the use of specific diameter thresholds to guide surgical decision-making across different ethnic populations [76].

Regarding cannulation technique, plastic cannulae have been associated with a lower incidence of infiltration and cannulation-related trauma compared to metal needles. Marticorena and colleagues reported that infiltration events occurred 2.3 times more frequently with metal needles, with most complications linked to sudden involuntary patient movement, and the flexible design of plastic cannulae after vessel entry may reduce transmission of mechanical stress to the vessel wall [77].

A study showed that higher substitution volumes were obtained at the same blood flow rate with plastic cannulae than with metal needles during online hemodiafiltration, suggesting that plastic cannulae are an option for achieving high-volume hemodiafiltration for patients with low blood flow rates [78].

In Japan, plastic cannulae have been used extensively for over two decades, with approximately 300,000 patients undergoing dialysis thrice weekly reporting minimal adverse outcomes. In contrast, use in Europe and other developed regions remains limited, often due to factors such as higher costs and the need for specialized training [79].

Important gender differences were widely demonstrated in specific medical conditions, and knowledge that many aspects of CKD manifest differently between men and women is increasing. CKD is more common in women, probably due to longer life expectancy and inaccurate GFR estimation, but women are less likely to be receiving HD, possibly due to faster decline of kidney function in men and psycho-socioeconomic factors [80].

The female longer life expectancy in the general population has been demonstrated to be reduced in hemodialysis, resulting in a cancelled or reduced survival advantage compared to males. Longevity on HD is directly proportional to the quality of hemodialysis, which in turn depends on the reliability and integrity of the vascular access, and vascular access also showed sex-dependent distinctions with AVFs less prevalent in females compared to males [81].

Detection and Management of Failing Fistulas

Routine monitoring is essential for early identification of fistulas at risk of failure. Physical examination during dialysis, assessing thrill, collapse on elevation, and pulse augmentation with venous occlusion, helps identify inadequate outflow from venous stenosis or reduced inflow. Contemporary surveillance relies primarily on Doppler ultrasonography or ultrasound dilution performed at the time of dialysis [82].

Patients should be referred for diagnostic fistulography when fistula dysfunction is suspected on a clinical basis or is detected. The practice of prophylactic intervention on significant stenosis detected by surveillance but not yet impeding effective dialysis remains controversial, though some studies have shown that prophylactic angioplasty on subclinical stenosis reduces rates of thrombosis [83].

Percutaneous angioplasty is the mainstay of treatment for dysfunctional arteriovenous fistulas, with as many as 90% of non-maturing fistulas progressing to functioning accesses with intervention. Primary patency at one year following angioplasty ranges from 40 to 60% in studies of immature fistulas salvaged by angioplasty, though younger fistulas have shorter periods of primary patency after the procedure [84].

Stents were recently approved for AVF stenosis, and while stenting is accepted for venous rupture or persistent bleeding, evidence for routine stenting of stenotic lesions beyond angioplasty is mixed. Stenting appears more beneficial in AV grafts than AV fistulas, and one retrospective study demonstrated a decreased need for angioplasty and longer time to maintenance angioplasty in cephalic arch stenosis treated with stent placement compared to balloon angioplasty alone [85].

While thrombosis often results in the end of a fistula's useful life, high rates of success are occasionally reported for endovascular treatment. Balloon thrombectomy, the first mechanical method for AVF thrombosis, dislodges thrombus into the central circulation but carries a theoretical risk of pulmonary embolism. Newer mechanical thrombectomy devices, such as rotating nitinol baskets, macerate thrombus which is then aspirated, and are increasingly used in practice [86].

Conclusion

Inflammatory biomarkers including NLR, PLR, SII, and CRP, along with the prognostic nutritional index and calcium-phosphorus product, have emerged as accessible and clinically meaningful predictors of arteriovenous fistula maturation failure in hemodialysis patients. When used in conjunction with preoperative vessel diameter assessment, these indices may enable effective preoperative risk stratification, guiding clinicians toward more individualized vascular access planning, timely nutritional and anti-inflammatory interventions, and closer postoperative surveillance in high-risk individuals. Given their low cost and wide availability, incorporation of these biomarkers into routine preoperative assessment protocols deserves further prospective validation in larger, multicenter populations [86].

References

1. Bikbov B, Purcell CA, Levey AS, et al. Global, regional, and national burden of chronic kidney disease, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet. 2020;395(10225):709–733.
2. Caputo BC, Leong B, Sibona A, et al. Arteriovenous fistula maturation: Physical exam versus flow study. Ann Vasc Surg. 2021;77:16–24.
3. Oliver MJ. The science of fistula maturation. J Am Soc Nephrol. 2018;29(11):2607–2609.
4. Kaller R, Arbănași EM, Mureșan AV, et al. The predictive value of systemic inflammatory markers, the prognostic nutritional index, and measured vessels' diameters in arteriovenous fistula maturation failure. Life (Basel). 2022;12(9):1447.
5. Murdeshwar HN, Anjum F. Hemodialysis. StatPearls. 2020.
6. Sars B, Van Der Sande FM, Kooman JP. Intradialytic hypotension: mechanisms and outcome. Blood Purif. 2020;49(1–2):158.
7. Rysz J, Franczyk B, Ławiński J, et al. Oxidative stress in ESRD patients on dialysis and the risk of cardiovascular diseases. Antioxidants. 2020;9(11):1079.

8. Vijaya KL, Aruna M, Rao SVLN, et al. Dietary counseling by renal dietician improves the nutritional status of hemodialysis patients. Indian J Nephrol. 2019;29(3):179–185.

9. Esteban-Fernández A, Villar-Taibo R, Alejo M, et al. Diagnosis and management of malnutrition in patients with heart failure. J Clin Med. 2023;12(9):3320.

10. Tavares AP dos SR, Mafra D, et al. Zinc plasma status and sensory perception in nondialysis chronic kidney disease patients. J Ren Nutr. 2021;31(3):257–262.

11. Sahathevan S, Khor BH, Ng HM, et al. Understanding development of malnutrition in hemodialysis patients: a narrative review. Nutrients. 2020;12(10):3147.

12. Gozubatik-Celik G, Uluduz D, Goksan B, et al. Hemodialysis-related headache and how to prevent it. Eur J Neurol. 2019;26(1):100–105.

13. Masud A, Costanzo EJ, Zuckerman R, Asif A. The complications of vascular access in hemodialysis. Semin Thromb Hemost. 2018;44(1):57–59.

14. He Y, Shiu YT, Imrey PB, et al. Association of shear stress with subsequent lumen remodeling in hemodialysis arteriovenous fistulas. Clin J Am Soc Nephrol. 2023;18(1):72–83.

15. Lok CE, Huber TS, Lee T, et al. KDOQI clinical practice guideline for vascular access: 2019 update. Am J Kidney Dis. 2020;75(4 Suppl 2):S1–S164.

16. Farrington CA, Robbin ML, Lee T, et al. Early predictors of arteriovenous fistula maturation: a novel perspective on an enduring problem. J Am Soc Nephrol. 2020;31(7):1617–1627.

17. Pivin E, Cunha Moreira Da Silva FA, Calanca L, et al. The vascular access of hemodialysis patients. Rev Med Suisse. 2019;15(639):439–443.

18. Pirozzi N, Scrivano J, Andracchio L, et al. Double guidewire technique: optimising endovascular revision of juxta-anastomotic stenosis in AV-fistulae. J Vasc Access. 2022;25(1):308–312.

19. Mishra B. Comparison of distal radiocephalic fistula vs proximal radiocephalic fistula. J Family Med Prim Care. 2021;10:132.

20. Kim H, Kim YS, Labropoulos N. Management of cephalic arch stenosis in hemodialysis access: updated systematic review and meta-analysis. J Vasc Access. 2024;26(4):1229–1240.

21. Sikora K, Zwolak A, Łuczyk RJ, et al. Vascular access perception and quality of life of haemodialysis patients. J Clin Med. 2024;13(8):2425.

22. Fuentes NES, Blanco JR, Garcia GQ, et al. A prospective study of factors associated with successful maturation of arteriovenous fistulas for hemodialysis. J Ultrason. 2024;24(98):1–7.

23. Malik J. When is arteriovenous fistula dangerous for hemodialysis patients? Kidney Dial. 2022;2(1):82–84.

24. Meola M, Marciello A, Di Salle G, Petrucci I. Ultrasound evaluation of access complications: thrombosis, aneurysms, pseudoaneurysms and infections. J Vasc Access. 2021;22(1 suppl):71–83.

25. Burnett CT, Nicholls G, Swinbank A, et al. Cephalic arch stenosis in the arteriovenous fistula: a retrospective analysis of predisposing factors. J Vasc Access. 2023;24(5):1084–1090.

26. Seck M, Bousso ES, Touré SA, et al. Thrombotic events and risk factors for thrombosis in polycythemia in Senegal. J Clin Haematol. 2023;4(1):1–8.

27. Marques MG, Ponce P. Pre-operative assessment for arteriovenous fistula placement for dialysis. Semin Dial. 2017;30(1):58–62.

28. Norton de Matos A, Sousa C, Teixiera G. Doppler ultrasound in vascular access for haemodialysis. Porto: Gráfica de Paredes; 2023.

29. Al-Jaishi AA, Liu AR, Lok CE, et al. Complications of the arteriovenous fistula: a systematic review. J Am Soc Nephrol. 2017;28(6):1839–1850.

30. Lapić I, Padoan A, Bozzato D, Plebani M. Erythrocyte sedimentation rate and C-reactive protein in acute inflammation: meta-analysis of diagnostic accuracy studies. Am J Clin Pathol. 2020;153(1):14–29.

31. Kaller R, Russu E, Arbănași EM, et al. Intimal CD31-positive relative surfaces are associated with systemic inflammatory markers and maturation of arteriovenous fistula in dialysis patients. J Clin Med. 2023;12:4419.

32. Zahorec R. Neutrophil-to-lymphocyte ratio, past, present and future perspectives. Bratisl Lek Listy. 2021;122(7):474–488.

33. Yilmaz H, Bozkurt A, Cakmak M, et al. Relationship between late arteriovenous fistula stenosis and neutrophil-lymphocyte ratio in chronic hemodialysis patients. Renal Failure. 2014;36:1390–1394.

34. Usman R, Jamil M, Naveed M. High preoperative neutrophil-lymphocyte ratio and red blood cell distribution width as independent predictors of native arteriovenous fistula failure. Ann Vasc Dis. 2017;10:205–210.

35. Pasqui E, de Donato G, Lazzeri E, et al. High neutrophil-to-lymphocyte and platelet-to-lymphocyte ratios are associated with a higher risk of hemodialysis vascular access failure. Biomedicines. 2022;10:2218.

36. Bashar K, Zafar A, Ahmed K, et al. Can a neutrophil-lymphocyte ratio derived from preoperative blood tests predict arteriovenous fistula maturation? Ann Vasc Surg. 2016;35:60–67.

37. Smith RA, Ghaneh P, Sutton R, et al. Prognosis of resected ampullary adenocarcinoma by preoperative serum CA19-9 levels and platelet-lymphocyte ratio. J Gastrointest Surg. 2008;12(8):1422–1428.

38. Sarioglu O, Capar AE, Belet U. Relationship of arteriovenous fistula stenosis and thrombosis with the platelet-lymphocyte ratio in hemodialysis patients. J Vasc Access. 2019;21:630–635.

39. Franchin M, Muscato P, Piffaretti G, Tozzi M. Systemic inflammation index as useful tool to predict arteriovenous graft stenosis. J Vasc Access. 2024;25(2):474–480.

40. Hu B, Yang XR, Xu Y, et al. Systemic immune-inflammation index predicts prognosis of patients after curative resection for hepatocellular carcinoma. Clin Cancer Res. 2014;20(23):6212–6222.

41. Ren S, Xv C, Wang D, et al. The predictive value of systemic immune-inflammation index for vascular access survival in chronic hemodialysis patients. Front Immunol. 2024;15:1382970.

42. Yang P, Liu L, Yang Z, Zhang BF. Beyond the threshold: how PNI predicts survival in elderly hip fracture patients. SSRN. 2024;5123842.

43. Miyasato Y, Morinaga J, Inoue H, et al. Association between prognostic nutritional index and peritoneal dialysis discontinuation: a retrospective cohort study. Renal Replacement Therapy. 2023;9(1):58.

44. Barutcu Atas D, Tugcu M, Asicioglu E, et al. Prognostic nutritional index is a predictor of mortality in elderly patients with chronic kidney disease. Int Urol Nephrol. 2022;54:1155–1162.

45. Wada H, Dohi T, Miyauchi K, et al. Relationship between the prognostic nutritional index and long-term clinical outcomes in patients with stable coronary artery disease. J Cardiol. 2018;72:155–161.

46. Siddiqui MA, Ashraff S, Carline T. Maturation of arteriovenous fistula: analysis of key factors. Kidney Res Clin Pract. 2017;36(4):318–328.

47. Li P, Lai Y, Tian L, Zhou Q. The prognostic value of prognostic nutritional index in advanced cancer receiving PD-1/L1 inhibitors: a meta-analysis. Cancer Med. 2022;11(16):3048–3056.

48. O'Neill WC. The fallacy of the calcium-phosphorus product. Kidney Int. 2007;72(7):792–796.

49. Tüysüz ME, Dedemoğlu M. Calcium phosphate product level as a predictor for arteriovenous fistula re-operations in patients with chronic renal failure. Vascular. 2019;27(3):284–290.

50. Long J, Chen H, Huang Q, et al. Analysis of risk factors for late arteriovenous fistula failure and patency rates after angioplasty in hemodialysis patients. Transl Androl Urol. 2024;13(2):209–217.

51. Schlieper G, et al. Calcification in chronic kidney disease: an update. Nephrol Dial Transplant. 2016;31(1):31–39.

52. Yap YS, Chi WC, Lin CH, et al. Association of early failure of arteriovenous fistula with mortality in hemodialysis patients. Sci Rep. 2021;11:5699.

53. Ge L, Fang Y, Rao S. A retrospective case-control study on late failure of arteriovenous fistula in hemodialysis patients and prediction of risk factors. Comput Math Methods Med. 2022;2022:8110289.

54. Hu K, Guo Y, Li Y, et al. Oxidative stress: an essential factor in the process of arteriovenous fistula failure. Front Cardiovasc Med. 2022;9:984472.

55. Wärme A, Hadimeri H, Nasic S, Stegmayr B. The association of erythropoietin-stimulating agents and increased risk for AV-fistula dysfunction in hemodialysis patients. BMC Nephrol. 2021;22(1):30.

56. Tsiftsoglou AS. Erythropoietin (EPO) as a key regulator of erythropoiesis, bone remodeling and endothelial transdifferentiation of multipotent mesenchymal stem cells. Cells. 2021;10(8):2140.

57. Liu S, Wang Y, He X, et al. Factors affecting suboptimal maturation of autogenous arteriovenous fistula in elderly patients with diabetes: a narrative review. Heliyon. 2024;10(15):e35766.

58. Qiong T, Jha I, Bahrami A, et al. Proposed numerical and machine learning models for fiber-reinforced polymer concrete. Front Struct Civ Eng. 2024;18(8):1169–1194.

59. Thomas SD, Sideris A, Narroway H, et al. Long-term results of interwoven nitinol stents to treat radiocephalic anastomotic arteriovenous fistula stenosis. J Endovasc Ther. 2023;30(2):176–184.

60. Gan W, Zhu F, Mao H, et al. The effect of early conversion from central venous catheter to arteriovenous fistula on hospitalization and mortality in incident haemodialysis patients. J Vasc Access. 2023;25(6):1967–1974.

61. Zhao B, Wang H, Wang Y, et al. Type 2 diabetes increase the risk of arteriovenous fistula non-maturation, mediated by postoperative vascular hemodynamics. Int Urol Nephrol. 2024;56(12):3887–3894.

62. Huber TS, Berceli SA, Scali ST, et al. Arteriovenous fistula maturation, functional patency, and intervention rates. JAMA Surg. 2021;156(12):1111–1118.

63. Lee KN, Chen CA, Kuo C, Yang LY. Ankle-brachial index associates with arteriovenous fistula stenosis. J Vasc Access. 2024;26(2):525–530.

64. Kler A, Khambalia H, Pondor Z, et al. Smoking is associated with a higher complication and failure rate in arteriovenous grafts for haemodialysis. J Vasc Access. 2023;24(4):747–753.

65. Nguyen NM, Chanh HQ, Tam DTH, et al. Metformin as adjunctive therapy for dengue in overweight and obese patients. Wellcome Open Res. 2021;5:160.

66. Aragoncillo Sauco I, Hevia C, Manzano Grossi S, et al. Effect of preoperative exercise on vascular caliber and maturation of arteriovenous fistula. J Nephrol. 2021;34(3):763–771.

67. Dember LM, Beck GJ, Allon M, et al. Effect of clopidogrel on early failure of arteriovenous fistulas for hemodialysis: a randomized controlled trial. JAMA. 2008;299(18):2164–2171.

68. Wei S, Liu N, Fu Y, Sun M. Novel insights into modifiable risk factors for arteriovenous fistula failure and the importance of CKD lipid profile: a meta-analysis. J Vasc Access. 2024;25(5):1416–1431.

69. Duayer IF, Duque EJ, Fujihara CK, et al. The protein-independent role of phosphate in the progression of chronic kidney disease. Toxins. 2021;13(7):503.

70. Hou G, Yan Y, Li G, et al. Preoperative cephalic vein diameter and diabetes do not limit the choice of wrist radio-cephalic arteriovenous fistula. J Vasc Access. 2020;21:366–371.

71. Li Y, Yang J, Chen Y, et al. Prognostic nomogram for the patency of wrist autologous arteriovenous fistula in first year. iScience. 2024;27:110727.

72. Marticorena RM, Dacouris N, Donnelly SM. Randomized pilot study to compare metal needles versus plastic cannulae in the development of complications in hemodialysis access. J Vasc Access. 2018;19:272–282.

73. Cho A, Park HC, Kim DH, et al. Impact of needle type on substitution volume during online hemodiafiltration: plastic cannulae versus metal needles. Kidney Res Clin Pract. 2023;42(1):117–126.

74. Tito F, Davidson-Peck D, Roettger AD, et al. Hemodialysis patients and complications management costs in Italy: plastic cannulae a potentially cost-effective strategy. J Vasc Access. 2024;25(2):599–606.

75. Pinho-Gomes AC, Carcel C, Woodward M, Hockham C. Women's representation in clinical trials of patients with chronic kidney disease. Clin Kidney J. 2023;16(9):1457–1464.

76. Angelici L, Marino C, Umbro I, et al. Gender disparities in vascular access and one-year mortality among incident hemodialysis patients. J Clin Med. 2021;10(21):5116.

77. Malik J, Lomonte C, Meola M, et al. The role of Doppler ultrasonography in vascular access surveillance. J Vasc Access. 2021;22(1 suppl):63–70.

78. Viecelli AK, Mori TA, Roy-Chaudhury P, et al. The pathogenesis of hemodialysis vascular access failure and systemic therapies for its prevention. Semin Dial. 2018;31:244–257.

79. Yu H, Chi Y, Wang B. The efficacy of percutaneous transluminal angioplasty and arteriovenous fistula reconstruction for immature arteriovenous fistula. BMC Nephrol. 2023;24:361.