InSight Bulletin: A Multidisciplinary Interlink International Research Journal
Peer Reviewed International, Open Access Journal.
ISSN : 3065-7857 / Website: https://ibrj.us / Volume-3, Issue-5 / May - 2026

Original Article

Redefining the hemodialysis lifeline: evolution of vascular access from fistulas to needle-free connected systems

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Manuscript ID:
IBMIIRJ -2026-030503

Submitted: 09 Apr. 2026

Revised: 15 Apr. 2026

Accepted: 05 May 2026

Published: 31 May 2026

ISSN: 3065-7857

Volume-3

Issue-5

Pp. 21-30

May 2026

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OPEN ACCESS

Quick Response Code:

Web. https://ibrj.us

DOI: 10.5281/zenodo.21637373

DOI Link:
https://doi.org/10.5281/zenodo.21637373

Abstract

Ones the kidneys fail to filter out metabolic waste products from the human body, ESRD (end-stage renal disease) occurs. Hemodialysis (HD), renal replacement procedure, is essential in some cases. A rapid flow of blood should be over 200 mL/min is needed for effective HD, and this is only done by using proper vascular access. Right now, arteriovenous fistula (AVF), arteriovenous graft (AVG), and central venous catheter (CVC) the three that were used a major vascular access option. Regarding patency, likelihood of infection, challenges, as well as long-term effects, each one of the vascular access strategies includes pros & cons. Although providing the gold standard vascular access for hemodialysis, AV fistulas possess limitations like late maturation, recurrent needle punctures, as well as infection risk. Needles-free vascular access methods were developed as the outcome of new technological advancements, with the goal of lowering problems from repeated needle insertion and developing comfort for patients. The different hemodialysis access system approaches, particularly needle-free vascular access systems, are addressed in this narrative review. This analysis additionally introduces a concept called SHIVAT, that supports the construction of a safe needle-free vascular access system. Although this SHIVAT can also have some of the complications like stenosis as well as thrombosis and higher chances of risk of infections .so in this article we are providing our innovation idea and this approach trying to lower infection & problems. This review could improve existing knowledge about vascular access systems in HD and guide ESRD patients as well as medical professionals better understand the variety of vascular access choices.

***Keywords**: End-Stage Renal Disease; Hemodialysis; Vascular Access; Arteriovenous Fistula; Central Venous Catheter; Needle-Free Vascular Access; Infection Risk; Access Patency; Safe Hemodialysis Implantable Vascular Access Technology.*

Introduction

When the kidney fails, that is the GFR less than 15 ml per min. It is the last stage they must want to undergo a renal replacement therapy. They cannot survey without RRT. Hemodialysis is one of the most commonly used RRT therapy when the individual who is not able to do renal transplantation or who is waiting for an organ donor. Vascular access is considered as one of the most important for hemodialysis procedure without vascular assess the HD won't happen. It is essential to deliver effective blood flow during dialysis to remove metabolic waste products & excess fluid accumulation. As a result, adequate vascular access can be viewed as the "lifeline" for individuals receiving continuous hemodialysis. Research has shown that differences in outcome for patients and therapeutic procedures among dialysis groups are related to (1) distinct vascular access modes (1,2).

AV fistula (AVF), Arteriovenous graft (AVG) & central venous catheter (CVC) are now the 3 main vascular access approaches utilized in clinical practice. Because of its improved chronic patency, greatly decreased infection rates, and more efficiently overall clinical outcomes as compared to various other approaches, AVF is commonly considered the preferable vascular route (3–7). AVF will also have some limitations though, since it may result in slower maturation, ultimate failure, or problems including stenosis & thrombosis, especially in older individuals and those with significant vascular complications (8,9). AV graft can be utilised sooner after implantation when compared to the other vascular access. But they also have some limitations such as infection & thrombosis.

How to cite this article:
Perumal, P. J. N. & Shanmugam, S. S. (2026). Redefining the hemodialysis lifeline: evolution of vascular access from fistulas to needle-free connected systems. InSight Bulletin: A Multidisciplinary Interlink International Research Journal, 3(5), 21–30. https://doi.org/10.5281/zenodo.21637373

Central venous catheters (CVC) also have a highest risk of long-term side effects & catheter-related bloodstream infections though being commonly used for quick dialysis start-up (4, 10, 11). Especially individuals on maintenance dialysis, vascular access failure is still considered to be a major cause of hospitalization and frequent treatments (12–14). New advances in surgical nephrology & biomedical engineering have contributed to the creation of novel strategies targeted at enhancing patient satisfaction and vascular access endurance. Possible substitutes for traditional needle-based access methods include emerging technology relating to endovascular AV fistula formation methods and needle-free vascular access devices. These developments are intended to increase safety for patients in HD therapy, minimize difficulties associated with frequent cannulation and expand access (15–18).

Therefore, complete knowledge on both newer and current vascular access approaches is essential to improve vascular access management & increase success over on especially among patients receiving maintenance hemodialysis. This narrative summary provides a snapshot of current vascular access options; including AVF, AVG, & CVC, to further investigate innovative needle-free vascular access methods that may impact standard dialysis vascular access control in the future.

Types of Vascular Access for Hemodialysis

An important prerequisite of vascular access for successful administration of continuous hemodialysis is the development of a trusted vascular access. To effectively remove additional fluid and cellular metabolic waste materials throughout dialysis procedures, appropriate vascular access must ensure to produce enough circulation of the blood for extracorporeal circuit during HD(14). In current, there are mainly three types of vascular access for hemodialysis: arteriovenous fistula, arteriovenous graft, & central venous catheter. These approaches differ in terms of compliance such as, level of infection risk, and prolonged quality of life (19). Since the AV fistula is longer lasting and has a smaller chance of infection than other vascular access methods so the arteriovenous fistula is usually seen as the best method (17). Vascular architecture, the presence of comorbid conditions, and expected length of dialysis therapy should all be taken into account when selecting a vascular access (7). The people who are all getting HD often experience problems like access-associated issues despite improvements in vascular access regulation and dialysis procedures. HD adequacy may be challenged due to problems like stenosis, thrombosis, infection, & access abnormalities, which often call for further interventional or surgical operations (17). Therefore, careful preparation and the right choice of vascular access are required.

AV FISTULA (AVF):

Definition:

An arteriovenous fistula (AVF), which usually develops on the hand, it is done via surgical connection between an artery & a vein that permits blood from the arterial system to travel straight into the venous circulation and permits the vein to dilate and strengthen it for frequent cannulation from hemodialysis(20–23). Compared to other vascular access, this method will provide greater life expectancy & reduce the chances of infection. In this procedure, they used their own artery and vein instead of a synthetic material. (1,21,24).

Physiology:

The unexpected redirection of blood from the arteries into venous circulation during AVF formation leads to major physiological changes inside the wall of the vessel, such as elevated shear stresses, endothelial stimulation, & nitric-oxide-mediated vascular remodelling (22,23,20). The fistula can handle the large blood flow rates that are necessary for successful extracorporeal circulation during hemodialysis owing to these adaptation physiologic processes, which cause rising venous dilatation & a normal wall hardening (21, 25, and 26).

Hemodynamic Mechanisms and Maturation:

After a fistula is created, the vein itself undergoes the functional structural modifications known as AVF maturation. At this time, elevated flow of blood promotes vein dilatation, vascular reconstruction, & enhanced vessel compliance; each one of these processes is essential for dialysis cannulation (22,23,26). Maturation failure is one of the most common clinical problems in hemodialysis patients; research indicates that a failure of newly created fistulas is mainly due to insufficient blood flow to the access site so that less blood will reach the extracorporeal circuit in dialysis use (22,26). Since AVF has better chronic patency & fewer infections compared to AV grafts and central venous catheters, this is often considered as the most effective options among the current vascular access strategies (25, 24, and 20). In addition, contrasted with persons utilizing catheter-based access, clinical studies have found that individuals dialyzing via AV fistula exhibit better survival results & lower mortality rates.

Fig 1 Fistula hand for Hemodialysis

Clinical Outcomes:

Since AVF has better chronic patency & less infections compared to AV grafts and central venous catheters, this is often considered as the most effective options among the current vascular access strategies (25, 24, 20). In addition, contrasted with persons utilizing catheter-based access, clinical studies have found that individuals dialyzing via AV fistula exhibit better survival results & lower mortality rates(25,27,28).

Fig 2 connection of needle for hemodialysis in AV fistula

Complications of Arteriovenous Fistula (Avf):

When arteriovenous fistulas are considered to be the ideal vascular access for prolonged dialysis, both efficacy and durability can be compromised by a number of problems. One of the most common adverse reactions is stenosis, which usually arises from neointimal hyperplasia in the venous drainage path & forces the lumen of the vessel to slowly narrow, thereby decreasing blood flow through the access (5,29,27). Of importance stenosis may finally lead to thrombosis if ignored left untreated. This is an additional main cause of AVF dysfunction & often requires immediate endovascular or surgical treatment in order to restore normal vascular access patency (29,30). Dialysis accessing steal syndrome, that happens whenever excessive amounts of blood from the arteries flows across the fistula & produces distant limb ischemia which presents as severe pain, chilly sensations, or neurological symptoms in the limb that is affected, is another medically significant consequence(30,31).

Also, repetitive needles insertion throughout dialysis treatments can weaken the arterial wall & cause aneurysms thereby raising the a complete rupture or epidermal collapse at the fistula location (5). Although the AVF is gold standard vascular access compared with graft & central venous catheter, although bacterial infection and localized infections can still happen and have to be treated without delay (5, 32).

Arteriovenous Graft (AVG)

1. **Definition & Structure:**

Whenever native blood vessels are not suitable for the formation of an arteriovenous fistula, an arteriovenous graft (AVG) is performed. It is a surgically formed vascular access when an artery is linked to a vein by introducing an artificial graft, usually made from stretched polytetrafluoroethylene (PTFE). The synthetic graft acts as a synthetic vascular conduit that allows regular blood from the arteries to travel via the veins to provide adequate blood supply for HD therapy. The synthetic graft acts as an artificial channel that permits normal blood from the arteries to travel through the venous system to ensure adequate blood supply during standard HD treatment (14, 33, and 34).

For creating a subcutaneous route that is capable of being continuously punctured for regular dialysis sessions, AV grafts are usually anatomically placed in the upper part of the body in a loop or linear shape. Arteriovenous grafts usually be functional more quickly after implant than AV fistulas, which require native vessels to get mature. Still, their long-run stability is not as good due to a greater likelihood of stenosis, thrombosis, as well as infection (14, 33, and 34).

2. **Pros Of A Vascular Access Graft(AVG):**

Though compared to AV fistulas, grafts typically maturation faster require little time to form. The main advantage of AVG over traditional is that it makes feasible to start daily dialysis sessions sooner since it requires a shorter period to get activated. Specifically, a frequently cannulated procedure could be done within a few weeks after deployment.(12,20).

Among CKD stage 5 individuals with poor & tiny vessels, or a history involving access failure, an AV graft was performed. This is most commonly done when the AV fistula is not possible for such individuals, then move to the next options of AV graft. In these conditions, artificial grafts give a lifelong vascular channel that allows regular maintenance and offers enough blood supply for dialysis (12, 20).

3. **Clinical Outcomes Of Arteriovenous Graft (AVG):**

When we see the clinical outcome between AV fistula and AV graft. Complications & long-term survival are the two main differences. Based on several kinds of studies, AV grafts usually have less favourable primary as well as secondary patency rates compared to AV fistulas. The stenosis and thrombosis will most commonly occur in the graft- vein anastomosis .This can lead to vascular access dysfunction (11, 35, and 10).

The infection and graft related complications are most commonly due to synthetic graft material. This often goes for surgical or endovascular procedures to provide adequate dialysis and access patency(35,10).

Regarding all of this, AV grafts seem to be a viable option for HD accessible among those with inadequate native arteries, providing a reliable replacement for prolonging dialysis therapy when fistula procedure is not viable option (11,10).

4. **Complications Of The Arteriovenous Graft (AVG):**

In general, AV grafts present more problems than AV fistulas. Even so, it is the most appropriate option for those who were insufficient to have an arteriovenous fistula. Some of the most common problems in AV graft are stenosis, which is usually occurring in the graft vein Anastasia. This can further lead to the narrowing of the vascular lumen over a time and hence limit the blood flow through the access. Vascular graft stenosis, which often arises near the graft-vein connection point as an outcome of neointimal tissue hyperplasia, is one of the most prevalent issues. There may be a chance of vascular lumen to stenosis, so that only a smaller amount of blood that may pass through the access to extracorporeal circuit (35,10).

Thrombosis will occur most commonly from untreated stenosis. Which may lead to sudden loss of vascular access function is another serious complication. Certain surgical procedures, such as thrombectomy/angioplasty, are often necessary to solve these problems (11,10).

Central Venous Catheter (CVC):

1. **Definition And Structure**

Actuality, intravascular catheters are those commonly referred to as central venous catheter / CVCs. This kind of vascular access was used for hemodialysis patients who need an immediate vascular access and to start the dialysis immediately after the implantation of vascular access or who are still without access to permanent vascular access, such as a fistula or graft. Commonly the internal jugular vein (IJV) is used to insert catheters. It is the primary option, but it may get vary depending upon the patient's medical condition & clinical outcomes; the femoral or subclavian veins can also be used(16,34).

For preserving flow of blood during hemodialysis, the HD catheters usually have two lumens that carry vein & arterial blood separately to the extracorporeal circuit. These are composed of biocompatible and flexible components like polyurethane as well as silicone. They CVC are broadly classified into two types: tunneled cuffed catheter; this type of catheter is mainly used for the long-term utilization; they contain subcutaneous cuff to fix and stabilize them and so the infection can be reduced. The second type of catheter is non- tunneled catheter they were used only for temporary access (16,34).

2. **Advantages And Clinical Use Of Central Venous Catheters (CVC):**

CVC usually has several advantages when compared to the other vascular access. Particularly when emergency dialysis therapy is required. One of the important advantages is that they offer instant access; there is no need for maturation period like AV fistula & graft. This is performed whenever there is a sudden increase in the serum electrolyte, metabolic changes like acidosis & fluid overload requiring further RRT (36, 37).

Further, CVCs have a common application as a short-term vascular access option for individuals who have been waiting for a permanent access, namely AV fistulas or grafts, to develop. Furthermore, if surgery administration of permanent access is not viable, catheter may be used in individuals who have acute coexisting conditions, weakened vascular architecture, especially multiple prior access failures. Also, insertion of a catheter is a relatively simple but less invasive method that is typically carried out with fluoroscopic / ultrasound supervision, so this makes it especially useful for patients with serious illnesses in ICU environments who require HD(36,37).

3. **Clinical Outcomes Of Central Venous Catheters (CVC):**

When compared to fistula/graft, the central venous catheter shows various clinical results. Though they provide immediate vascular access and they were often used for the urgent initiation of HD. When a long- term insertion of central venous catheter may lead to infection some of the studies proven that have a chance of dysfunction of the catheter /insufficient blood flow. Which may threaten the effectiveness and sufficiency of the treatment (36, 38).Catheter- related blood stream infection is the one of the most common infections (CRBSIs), which may lead to hospitalization and morbidity among HD patients(1,39). Such negative effects bring focus toward the disadvantages of prolonged insertion of catheters also underline how important it is to shift individuals to standard permanent vascular access if possible to improve over a long period of therapeutic outcomes (40).

4. **Central Venous Access Device (CVAD) Complications:**

Many problems linked to central venous catheters having a substantial negative influence on outcomes for patients that restrict long-term continued use of HD. A single of the most hazardous adverse reactions is catheter-related bloodstream infections, which remain to be a significant cause for hospitalization as well as morbidity associated with routine hemodialysis subjects. A greater chance of both infection / systemic bacteremia is triggered by the presence of an external instrument, repeated catheter handling, and biofilm formation on the catheter's site (41, 42).

This catheter cause thrombosis is another major issue that may occur whenever the fibrin sheath develops surrounding the catheter, if an intravenous clot forms. Lower the blood flow, catheter malfunction, & leads to reduced dialysis treatment may arise from this condition, often undergoing thrombolytic treatment or just catheter removal (36).

Central venous stenosis, a problem brought on by endothelial injury with prolonged artery wall inflammation, is also related to prolonged CVC usage. Chronic dialysis care might get more difficult due to venous hypertension, limb swelling, along with problem obtaining for later vascular access (37).

Especially after the insertion procedure or during extended use, mechanical problems that involve catheter positioning error, twisting, and accidental dislocation can also develop. Catheters performance may be affected by these issues, requiring the catheters to reposition nor exchange.

Fig 3 Central Venous Catheter (CVC)

Kind of Accessibility	Patency (durability through time)	Chance of Infection	Universal usage case
Arteriovenous Fistula (AVF)	(Best) greatest primary as well as secondary vascular patency.	(The Minimal)	Beginning choice for long-lasting hemodialysis; optimal for persons having good blood vessel structures.
Arteriovenous Graft (AVG)	(moderate-High) Due to narrowing & bleeding, AV Graft (AVG) is less compared to AVF	(Moderate–High)	Therefore, it is utilised when the standard AVF is insufficiently (low-quality veins, elderly, or prior failure); it is quicker then AVF.
Central venous catheter	(Bad) Highest failure rate & malfunctions levels	(Highest)	For intensive care unit or sick cases; a common bridge till AVF/AVG is available; urgent or short-term access

Table 1: Comparing the Different Types Of Vascular Access Kind Of Accessability, Patency, Chance Of Infection, Universal Usege Case.

Advanced Hemodialysis Access Methods

1. **Endovascular Av Fistula:**

The new, least-invasive Endovascular Arteriovenous Fistula (endoAVF) device creates AV fistulas via percutaneous catheter procedure rather than conventional methods. This approach offers a lower aggressive volition for the development of access in some individualizes by precluding open surgical procedures & reducing postoperative damage to apkins. EndoAVF, as the name indicated, will be carried out as normal with imaging observation to establish a relationship between conterminous modes & highways typically without demanding operation. In addition, since suitable roadway confines as well as closeness are crucial variables impacting surgical procedure feasibility a comprehensive assessment of vascular structures is needed for effective endoAVF development(43).

Similarly to the Ellipsys Vascular Access Technology & WavelinQ EndoAVF Vascular Access System, endoAVF devices use thermal or RF radiation to build the AV anastomosis. These types of systems are an implicit relief for surgically made fistulas as clinical examinations have shown that they are related to elevated specialized success rates, faster recovery times, plus favourable development issues. Also, individuals with limited vascular structure and those considered high - threat for surgical procedures might have lesser options for access to vascular systems because of endoAV(44,45). But this also gets failure due to infection and thrombosis.

2. **Needly Free Vascular Access System:** For the purpose to minimising demand for routine injections throughout hemodialysis while increasing the comfort of patients, needle-free vascular insertion techniques were developed. The application of standard implanted vascular access ports, including Dia lock, Life Site, as well as Hematite, was mainly eliminated because of a high number of common complications, such as a typical infection, thrombosis or a device malfunction, plus expense-related problems, which inhibited prolonged clinical performance (16).

Fig 4 SHIVAT device

Recent advances in technology, like the Safe Hemodialysis Implantable Vascular Access Technology (SHIVAT), were created according to such constraints. SHIVAT is a graft-based and surgically placed vascular access port that enables needle-free access into the extracorporeal circuit through a twist-lock mechanism, sealed connection device. Through the titanium body is connected with two arterial & venous channels linked by a graft material, the device allows for regulated flow of blood by avoiding the requirement for frequent artery punctures (46).

Initial testing showed that the instrument was practical and functional, providing sufficient bloods flow & a safe connection free from issues such as air embolism and leakage. In addition, the sealed-system layout could enhance both comfort as well as ease of operation by reducing handle procedures as well as risk of infection. Here remain a few restrictions however; to attain the optimal blood supply levels needed for normal human dialysis, further investigation is required as the proof at present is limited to animal research. New dangers, including infection, bleeding, and prolonged device-associated problems, are caused by the need for a surgical implant with the application of a vascular graft. These limitations correspond to broader findings indicating prosthetic devices and inserted vascular access equipment had greater rates of problems than native accessible alternatives(16,46). Future developments should concentrate on enhancing devices quality, improving hemodynamic efficiency, with proving safety and efficacy over the long term in individual clinical investigations. Moreover, these innovations could provide simpler handling as well as Possible use in self-care settings or home-based dialysis treatments, since such applications remain being developed.

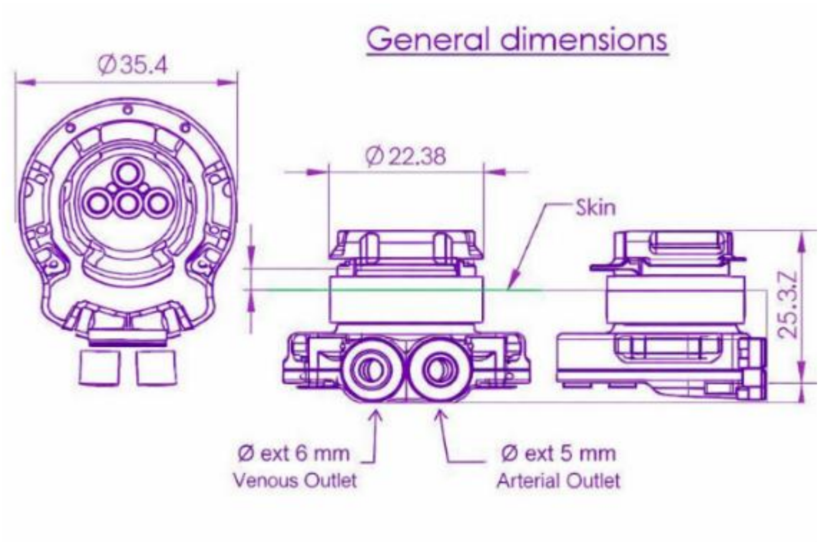

Fig 5 SHIVAT working principle

Our Latest Advancement:

A different alteration is proposed to enhance infection prevention and quick problem detection, based upon the limitations present in current implantable vascular access methods. The tool's inner titanium body & external port connection are divided by a self-sealable sterile wall. For limiting bacteria migration after recurrent insertions, this barrier is designed to act to provide a protected barrier along with reduce the likelihood of infection associated when in use.

To allow continuous tracking of the flow of blood inside the device, the proposed system additionally includes a tiny flow-sensing microchip that is embedded around a titanium-based body. This feature could make it simpler to detect flow abnormalities at an early stage, allowing early identification of issues including thrombosis with stenosis before clinical impairment takes place.

Further, an additional layer of germ prevention is recommended by applying an antimicrobial surface coating on the opening port of the device to avoid adherence of bacteria / biofilm formation. A multifunctional approach focused on improving device durability, security, plus clinical outcomes include a physical sterile barrier, active flow monitoring and antimicrobial surface enhancement. But beyond any practical acceptance, the proposed innovation requires additional studies to evaluate biological compatibility, durability over time, biosensor accuracy, and economic viability. It also needs to have been verified by laboratory and clinical studies. Most infection happens during connections a safer device

Dialysis tubing line

↓

The sterile gate that locks itself

↓

Then open blood circuit

Estimated Budgect For One Shivat Sensor Model:

Component	Purpose	Approx Cost (₹)
Ultrasonic transducers (2 pieces)	Send & receive ultrasound signal	₹800 – ₹1,600
Ultrasonic flow sensor chip (e.g., TI TDC1000)	Measures transit time of ultrasound	₹650 – ₹1,200
Microcontroller	Processes sensor data	₹250 – ₹650
NFC / RFID chip	Wireless communication	₹160 – ₹400
Mini antenna coil	Sends signal outside body	₹80 – ₹240
Small PCB board	Holds electronic components	₹160 – ₹400
Biocompatible coating / encapsulation	Protects electronics in body	₹400 – ₹800

Minimum total= ₹2,500 Maximum= ₹5,290

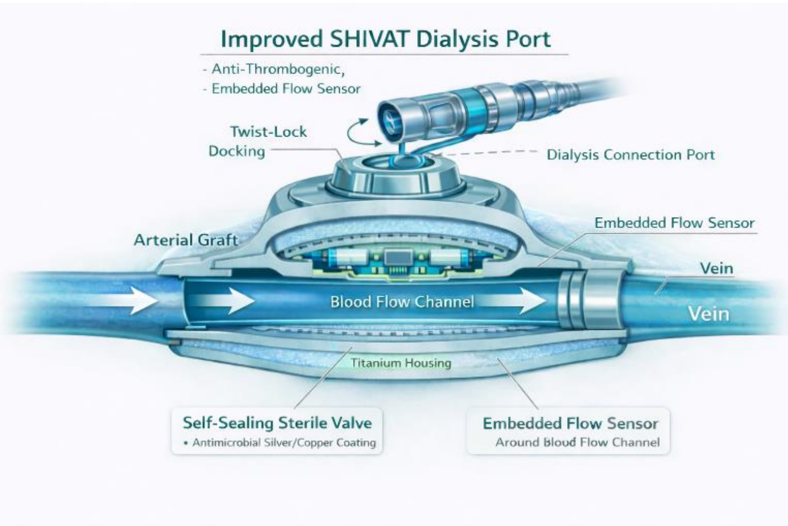

Fig 6 My Innovation In SHIVAT

Conclusion:

That suffering from advanced renal disease, vascular access is their "lifeline" throughout is essential to a proper dialysis treatment. Due to its superior quality and lower risk of infection, the arteriovenous fistula (AVF) remains to be the gold-standard option for vascular access. Although that they have a greater likelihood of infection as well as thrombosis, arteriovenous grafts (AVG) are beneficial in individuals with poor native arteries. Although they offer immediate access to dialysis, central venous catheters (CVCs) have the greatest incidence of problems including infections of the bloodstream. Less invasive alternatives to standard surgical fistula formation are offered by endovascular AV fistula procedures. In order to increase the patient life quality &

lessen the discomfort related to repetitive needle insertions, needle-free vascular access techniques were created. An new implantable needle-free access technique with better security and regulated blood circulation is the SHIVAT system. We suggested invention, which includes a flow-detecting microchip, antimicrobial coating, as well as sterile self-sealing barriers, may help prevent infections and detect thrombosis early. For long-term hemodialysis care, secure, long-lasting, plus user-friendly vascular access devices must be invented through future clinical research and advances in technology.

Future Developments

Future vascular access technologies for hemodialysis will focus on improving safety, comfort, and long-term durability. Needle-free vascular access systems may reduce repeated needle puncture pain and lower infection risk in dialysis patients. Smart biosensor-based devices could help detect stenosis, thrombosis, and blood flow changes at an early stage. Advanced antimicrobial coatings and biocompatible graft materials may improve vascular access patency and reduce complications. Endovascular AV fistula creation techniques are expected to become more common because they are minimally invasive. Innovations such as SHIVAT may provide safer implantable vascular access systems for future home and maintenance hemodialysis. Further clinical studies and biomedical engineering research are required to make these technologies safe, affordable, and widely available.

Acknowledgment

The authors express their sincere gratitude to Dhanalakshmi Srinivasan University, Tiruchirappalli, for providing the academic environment and necessary support to carry out this review study on hemodialysis vascular access. The authors are deeply thankful to the faculty members of the Department of Renal Science and Dialysis Technology for their valuable guidance, encouragement, and constructive suggestions throughout the preparation of this manuscript.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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