Li et al. BMC Nephrology (2025) 26:252
https://doi.org/10.1186/s12882-025-04182-4

BMC Nephrology

REVIEW

Open Access

# Prevailing insights into anastomotic angles of surgically created arteriovenous fistulas: a literature review

Xinyang Li[1†], Chong Liu[1†] and Haidi Hu[1*]


## Abstract

**Objective** An arteriovenous fistula (AVF) is the most common type of vascular access, given its low infection rate, few complications, good patency potential, and long service life. Although preferred for most patients with chronic kidney disease (CKD), those undergoing dialysis continue to experience AVF surgical failures and complications, with 60% of AVFs failing to mature. The anastomotic angles chosen for AVF creation are usually ones that surgeons find easiest to manually control. At present, many sources have confirmed that variations in anastomotic angle culminate in differing geometric parameters of perianastomotic blood vessels, thus affecting the AVF maturation process.

**Methods** This publication was intended to highlight the progress achieved with respect to AVF anastomotic angle conventions through collective outcomes of clinical analyses, basic research, computational fluid dynamics (CFD) studies, and VasQ external stent trials. The insights gained may well fuel clinical efforts to implement more durable blood channels in patients with end-stage kidney disease (ESKD). For our purposes, we described anastomotic angles as acute (< 30°), intermediate (30–70°), or obtuse (> 70°), rather than invoking mathematical standards.

**Results** In clinical research, two studies support the acute angle, three studies support the intermediate angle, three studies support the obtuse angle. In CFD research, one article supports the acute angle, six articles support the intermediate angle, and one article supports obtuse angles.

**Conclusions** Our analysis demonstrates an intermediate angle of 30–70° would be an optimal angle for AVF anastomosis, according to the existing research results. VasQ external stent devices have yielded superior AVF maturity and patency by maintaining anastomosed arteries and veins at angles of 40–50°, resulting in improved patient outcomes clinically, which supports the use of the device in the clinical practice.

**Clinical trial number** Not applicable.


**Keywords** Dialysis, Arteriovenous fistula, Anastomotic angle, Chronic kidney disease

†Xinyang Li and Chong Liu contributed equally to this work.

*Correspondence:
Haidi Hu
hdhu@cmu.edu.cn
[1]Department of General and Vascular Surgery, Shengjing Hospital of China Medical University, Shenyang, Liaoning Province 110004, China

## Introduction

Chronic kidney disease (CKD) has drawn much attention due to an increasing prevalence. End-stage kidney disease (ESKD), being the ultimate outcome, has also become a public health problem worldwide [1]. Hemodialysis is effective in treating ESKD, if there is reliable vascular access in place for blood exchange several times weekly [2]. At present, the primary long-term options for hemodialysis vascular access are arteriovenous fistula (AVF), central vein catheter (CVC), and arteriovenous graft (AVG). The low infection rate of AVF, in addition to its few complications, improved patency, and long service life, have made it the most common choice and the preferred route for many patients with CKD [3].

Typically, AVF creation (Fig. 1) involves an upper arm or forearm, using the patient's own blood vessels to form an arteriovenous (AV) shunt. Arterial blood of sufficient pulsatile flow is thus artificially diverted to superficial veins for easy puncture, while establishing an ideal cardiopulmonary bypass and ensuring conditions for blood purification treatment [4]. Unfortunately, those patients in need of dialysis continue to suffer from AVF surgical failures or complications, with up to 60% of fistulas failing to mature [5]. Such issues impair or disrupt AVF function, halting vital treatment and imposing burdens of cost and psychological stress [6].

The angle chosen for AVF anastomosis is typically one that a surgeon deems easiest to manually control [7]. Data from a number of sources indicate that variations in AVF anastomotic angles impart differing geometric parameters within perianastomotic blood vessels, which clearly may influence fistula maturation and impact clinical outcomes. However, the optimal AVF anastomotic angle remains a topic of debate in medical circles.

In this publication, we examined advances into AVF anastomotic angle conventions, drawn from findings of clinical analyses, basic research, computational fluid dynamics (CFD) studies, and VasQ external stent trials. Our intent was to provide insights from various vantage points, helping clinicians create more durable vascular access for patients with ESKD. Of note, we described anastomotic angles as acute (< 30°), intermediate (30–70°), or obtuse (> 70°), rather than relying on mathematical standards referenced in available reports.

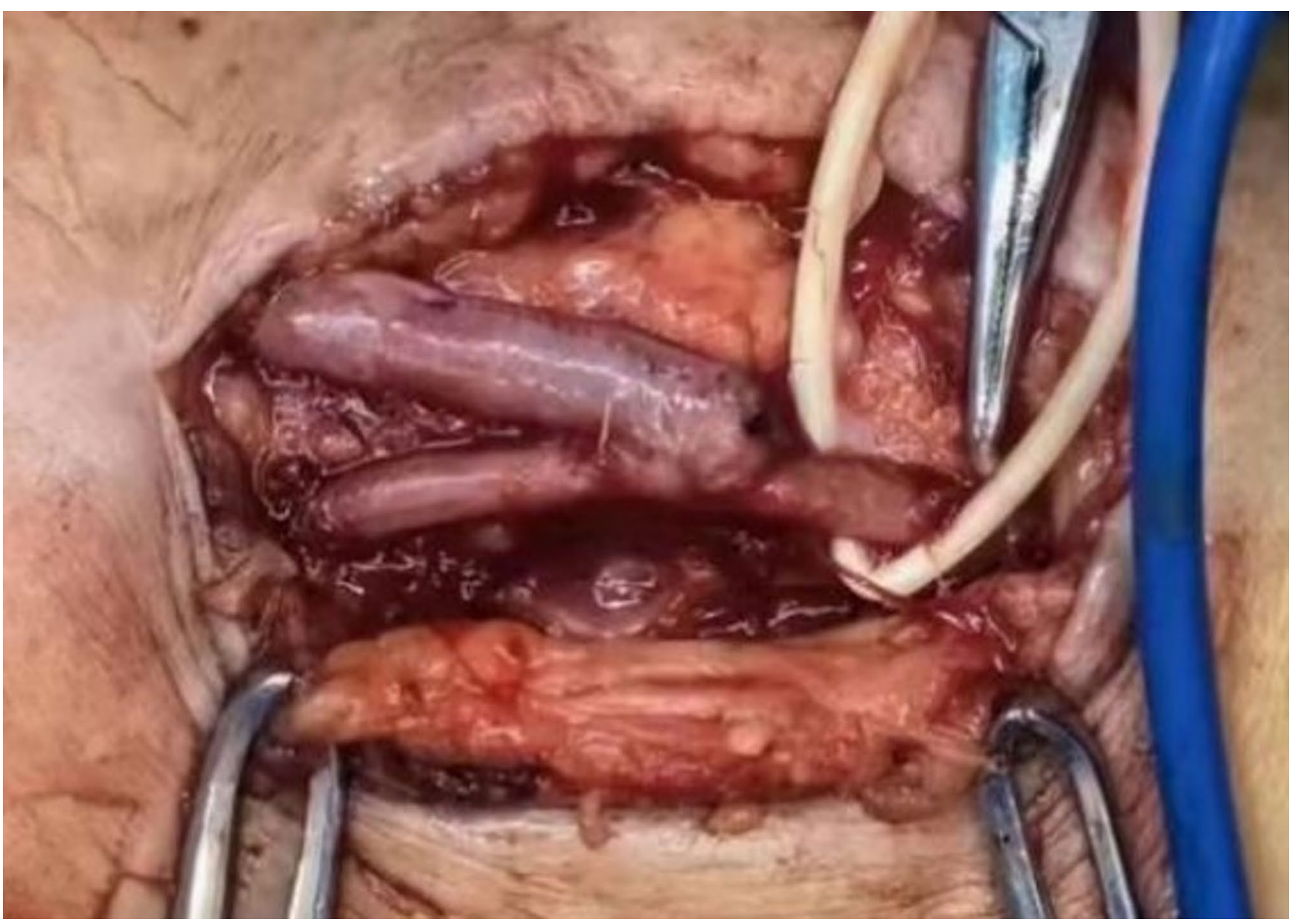

**Fig. 1** Arteriovenous fistula (AVF) creation

**Table 1** Summary of research perspectives on AVF anastomotic angle

| Research type | Acute angle (< 30°) | Intermediate angle (30–70°) | Obtuse angle (> 70°) |
|---|---|---|---|
| Clinical research | 2 | 3 | 3 |
| CFD research | 1 | 6 | 1 |

CFD, computational fluid dynamics; AVF, arteriovenous fistula

### Clinical research on AVF anastomotic angle

The angle of AV anastomosis has always been the focus of surgeons during AVF surgery, and it underscores the challenge of such procedures [8], being pivotal in determining operative success and subsequent AVF maturation (Table 1 and 2) [9]. For a period of ~2.5 years, Sadaghianloo et al. [10] conducted a prospective study of 149 patients with radiocephalic (RC-AVF) or brachiocephalic (BC-AVF) AVFs. Ultimately, they found that anastomotic angles ≥ 30° (vs. < 30°) conferred better clinical outcomes, suggesting that acute RC-AVF anastomotic angles were more likely to result in neointimal hyperplasia and anastomotic stenosis, requiring re-intervention. Such scenarios should rightly be avoided.

During long-term ultrasound monitoring of 14 patients with AVFs, Fiorina et al. [11] discovered that a 90° anastomotic angle corresponded with the fastest rate of anastomotic blood flow (up to 50 cm/s) and potentially played a positive role in AVF maturation. Rezapour et al. [12] have also developed a novel vascular image processing method as a direct and integrated solution for measuring relevant parameters (e.g., anastomotic angle and arterial diameter), without regard to hemodynamics. It was subsequently apparent that an anastomotic angle ≤ 30° is preferable for AVF surgery, effectively reducing the surgical failure rate and contributing to AVF maturity according to Rezapour et al. [12]. However, this is inconsistent with most other studies.

Currently, a three-dimensional vascular model generated via magnetic resonance angiography [13–16] is considered a promising approach to the study of vascular diseases. Unlike direct measurements tied to angiographic techniques, related errors are effectively reduced [17]. Yang et al. [18] have similarly adopted a novel approach to integrate patient-specific AVF contour information into CFD simulations. In analyzing 27 patients with RC-AVFs (for hemodialysis), they determined that an anastomotic angle > 46.5° may lead to blood flow disturbance and more severe vascular stenosis.

End-of-vein to side-of-artery (ETS) anastomosis is one of the most commonly used methods for AVF creation in clinical practice [19], and it is a procedural recommendation within guidelines of the European Society for Vascular Surgery [20]. Xu et al. [21] conducted a 3-year prospective study in 2023 to assess this particular strategy. Results were favorable at both 3 and 12 months postoperatively. In the final comprehensive analysis, anastomotic angle emerged as an independent predictor of primary patency and re-intervention accumulation rates, with 30–50° being optimal for anastomotic angles. Sivanesan et al. [22] have studied 25 patients with AVF anastomotic angles averaging 45°. AVF stenosis was categorized, based on three separate stenotic sites, but the relation between patient prognosis and anastomotic angle was not explored.

Another retrospective study by Lee et al. [23] has shown that patients ($n = 201$) undergoing RC-AVF surgery achieve significantly better primary and secondary patency rates if an obtuse (vs. acute) anastomotic angle is used, which is in direct contrast with abovementioned study details. This team also used a research-oriented

**Table 2** Clinical analyses of AVF anastomotic angle

| | Reference | Year | Patient total | Method | Recommended angle |
|---|---|---|---|---|---|
| 1 | Sadaghianloo et al. | 2015 | 149 | Primary patency at 1 year: 38% for <0–30°, 56% for ≥ 30°; Secondary patency at 1 year: 58% for <0–30°, 93% for ≥ 30°; Cumulative rate of juxta-anastomotic procedures at 1 year: 66% for <0–30°, 33% for ≥ 30° | ≥ 30° (intermediate and obtuse) |
| 2 | Lee et al. | 2016 | 201 | Primary, primary assisted, and secondary patency at 2 years: 45.7%, 76.1% and 89.9% in the classic AVF group and 3.2%, 80.1% and 84.1% in the obtuse AVF group | >90° (obtuse) |
| 3 | Fiorina et al. | 2017 | 14 | Ultrasound Vector Flow Imaging: 90° (2/9) with best mean velocity vectors | 90° (obtuse) |
| 4 | Rezapour et al. | 2018 | 48 | AVF maturation at 1 year: 43% for ≤ 30°; 18% for 30–50°; 23% for 50° | ≤ 30° (acute) |
| 5 | Yang et al. | 2020 | 27 | Hemodynamic parameters at stenotic lesion site | ≤ 46.5° (acute and intermediate) |
| 6 | Xu et al. | 2023 | 124 | Primary patency at 1 year: 83% for 30–50°, 58% for 50–70°, 65% for 135°; Secondary patency at 1 year: 90% for 30–50°, 84% for 50–70°, 84% for 135°; Cumulative rate of re-intervention at 1 year 10% for 30–50°, 34% for 50–70°, 26% for 135° | 30°-50° (intermediate) |

AVF, arteriovenous fistula

computer simulation to confirm their finding that an obtuse angle is the best configurations for AVFs, which we will revisit later in our discussion.

He et al. [24] also examined anastomotic angles of upper arm AVFs, which were larger than those of forearm AVFs, showing increases at postsurgical Weeks 1 and 6. However, the three-dimensional structures of forearm AVFs did not significantly change over time. These observations serve as valuable references for surgeons, helping to guide informed decisions.

Shenoy et al. and Bharat et al. [25, 26] both pioneered the piggyback straight-line onlay technique (pSLOT). This procedure calls for isolating the subcutaneous cephalic vein, ligating its distal end, carefully moving the proximal cephalic vein to upper part of radial artery, and anastomosing below-vein and above-artery to create an AVF. The anastomotic angle is adjusted to < 10°, with an anastomotic diameter > 5 mm. Studies show that pSLOT maneuvers stand to prevent type I stenosis of AVFs, reduce closed anastomosis problems, increase maturity rates of internal fistulas, and mitigate long-term complications due to high-flow velocity, thereby effectively improving AVF results [26, 27]. However, these studies are currently limited and outdated.

Most clinical studies to date support the use of intermediate or obtuse angles for AVF anastomosis, taking into account the structure of a patient's blood vessels, the caliber and quality of artery and vein earmarked for AVF creation, the surgeon's technique and expertise, and other factors. There are many evolving operative tactics that rely on optimal anastomotic angles for favorable outcomes. However, the number of cases is skewed (minimum, 14; maximum, 201), so their individual merits are relative. Based on sample size and study method, 30–50° would be best as AVF anastomotic angle. The preponderance of current clinical data (> 100 cases) suggests that intermediate or obtuse angles are associated with better clinical outcomes, although a "proper anastomotic angle" is still in need of investigation.

### Basic AVF research

Endothelial nitric oxide synthase (eNOS) is a major vasodilatory substance released by vascular endothelial cells [28, 29] that is capable of inhibiting neointimal hyperplasia in patients with AVFs [30, 31]. Activation of eNOS is induced by increased blood flow within vessels [32, 33]. Based on these fundamentals, Bai et al. [34] proceeded to construct an AVF animal model in rats (using carotid artery and jugular vein) in order to study ramifications of eNOS for AVF neointimal proliferation. In doing so, they examined specific anastomotic angles (acute, obtuse, and end-to-end [ETE]), determining that jugular vein neointimal area outflows were significantly larger for the acute-angle group, compared with obtuse-angle or ETE group members. In conjunction with Fig. 2, the following formula is currently a common formula for anastomotic angle calculation [35]:

$$Anastomoticangle = 57.3cos^{-}1\,\frac{a\cdot b}{|a|\,|b|}$$

In simpler terms, these vectors are measured from anastomotic initiation point to a straight-line distance, although precise values of *a* and *b* are not yet standardized.

As an example, Northrup et al. [36] defined the linear distances (*a* and *b*) as 2 mm in an animal study focused on sildenafil-promoted AVF maturation. Falzon et al. [35] have also studied various geometric structural problems related to AVF using mouse models and incorporating professional inter- and intra-variability analysis. They thus examined factors, such as the impact of angle vector on linear distance of the anastomosed interface, creating AVFs with anastomotic angles close to 90°. The investigators selected three values for linear distance, namely 0.5, 1.0, and 1.5 mm, finding no significant differences among them. Therefore, all three values are valid as reference standards.

Within the existing literature, there are few basic studies of AVF anastomotic angles. More comprehensive and in-depth probes are required to identify an anastomotic angle that aligns with principles of fluid mechanics.

### Computational fluid dynamics (CFD)-based AVF research

CFD has become an effective alternative tool for studying vascular physiology, one that features an array of simulation methods, offers noninvasive capabilities, and provides good visibility [37]. Moreover, the fundamental technology has reached a relatively mature stage, enabling one to simulate blood flow and generate high-resolution 3D images within a few hours [38]. CFD has also served as an important means of researching AVF-related elements [39], including AVF fluid dynamics [40], wall shear stress (WSS) [41], oscillatory shear index (OSI) [42], and other pertinent metrics. There have been several studies using various CFD methods to explore the impact of anastomotic angles on AVF viability (Table 3).

Prouse et al. [43] have configured CFD models and have duly contended that anastomotic angles of 60–70° provide the best hemodynamic conditions for RC-AVF maturation and long-term patency. In their hands, angles > 90° clearly failed to confer hemodynamic advantages. Stella et al. [44] have also observed a lower risk of AVF failure at anastomotic angles of 60° and 70°, which Prouse and colleagues [43] attribute to the fact that within this range, large anastomotic vortices and zones of stagnation arise. Areas of low WSS result, and the extent of vessel walls bearing high OSI levels is diminished at

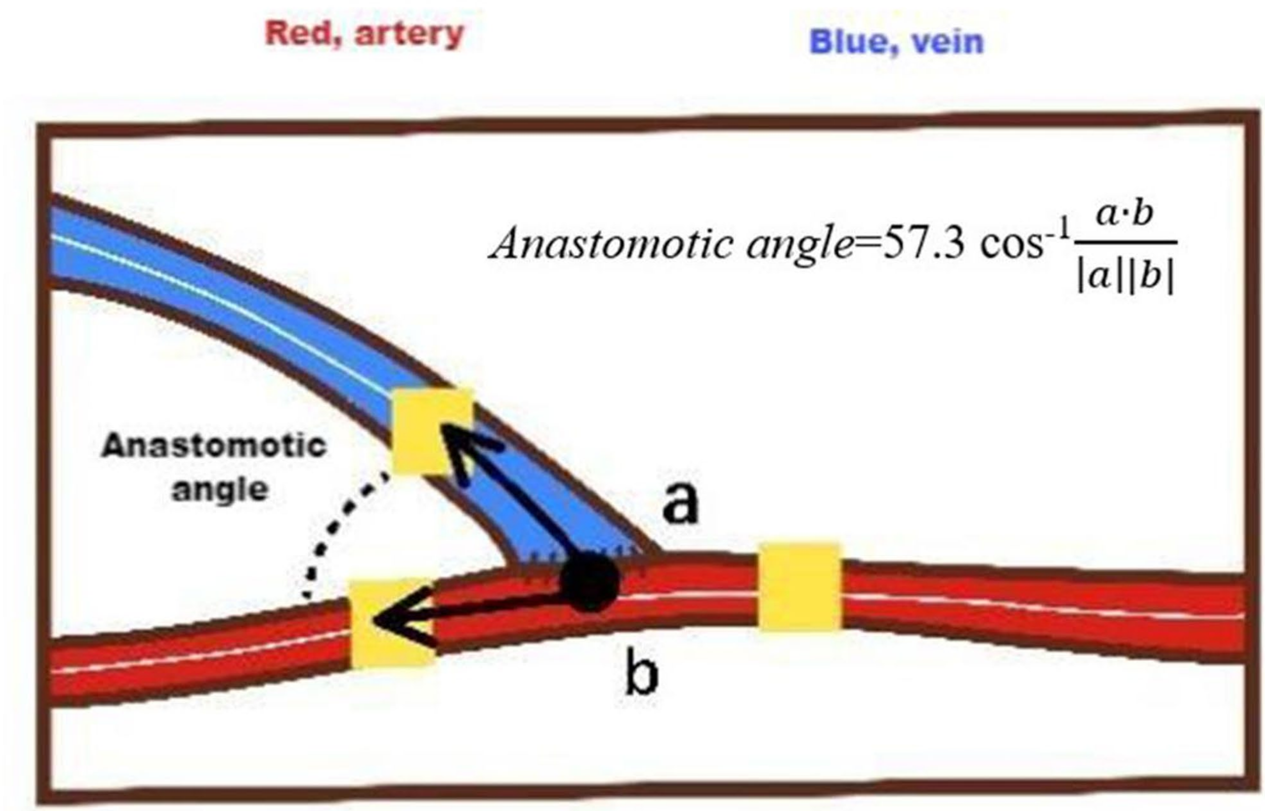


**Fig. 2** Common formula for anastomotic angle calculation

**Table 3** CFD studies involving AVF anastomotic angle

| | Reference | Year | Study parameter(s) | Recommended AVF anastomotic angle |
|---|---|---|---|---|
| 1 | Van et al. | 2010 | Pressure drop | 45° (intermediate) |
| 2 | Ene-Iordache et al. | 2013 | Velocity vector | 30° (intermediate) |
| 3 | Hull et al. | 2013 | Pressure drop, velocity vector, wall shear stress | 45° (intermediate) |
| 4 | Silva et al. | 2015 | Wall shear stress, oscillatory shear index, velocity | 25 ± 5° (acute) |
| 5 | Lee et al. | 2016 | Wall shear stress, velocity vector | >90° (obtuse) |
| 6 | Stella et al. | 2019 | Wall shear stress, oscillatory shear index, fluctuations in velocity magnitude | 60° and 70° (intermediate) |
| 7 | Carroll et al. | 2019 | Flow disturbance, arterial pressure and flow rate, velocity vector | 45° (intermediate) |
| 8 | Prouse et al. | 2020 | Velocity fields, wall shear stress distribution, oscillatory shear index | 60–70° (intermediate) |

CFD, computational fluid dynamics; AVF, arteriovenous fistula

anastomotic sites and initial venous segments. Larger acute angles consequently seem to promote balanced flow. In similar fashion, Cunnane et al. [45] have demonstrated that AVF models endowed with smaller anastomotic angles show lower WSS distributions and are characterized by forceful helical flow, with strong equilibria between helical structures.

Ene-Iordache et al. [46] have addressed the challenge of identifying disturbed AVF flow by creating CFD models. A smaller anastomotic angle of 30° seemed to improve disturbed-flow localization, suggesting that this angle holds potential as a clinical benchmark. Van et al. [47] have also used CFD experimentation to investigate the impact of anastomotic cross-sectional areas and angle magnitudes on AVF hemodynamics at flow rates of 600–1200 mL/min. They eventually documented an anastomotic angle of 45° as the most stable.

In another effort, Hull et al. [48] engaged CFD methods to validate AVF anastomotic structures, having emphasized that anastomotic angles are highly culpable in intravascular pressure drops. CFD models were constructed for patient groups designated as side-to-side (STS), 45° ETS and 90° ETS to compare parameters in a simulated environment, setting blood-flow velocity at 900 mL/min.

As they observed, STS and 90° ETS configurations exhibited higher venous outflow and tended to reverse arterial outflow. However, the 45° ETS design displayed reduced venous discharge, while averting arterial discharge reversal. In comparing WSS, the observed trend was a higher value for STS vs. 45° ETS, with 90° ETS registering lower still. Silva et al. [49] devised a CFD model as well to comprehensively analyze velocity field, WSS, and OSI, finding that AVF anastomotic angles of 25°±5° proved most suitable for clinical applications.

Although the CFD studies summarized above attest to the suitability of a smaller AVF anastomotic angle for clinical application, it is important to note that some scholars may not share this perspective. Carroll et al. [50] have produced a CFD model for vessels 5 mm across, revealing a more overt blood-flow interference by an acute-angle (vs. a smooth-vein loop) anastomosis during the full pulse cycle. In addition, it appeared that gradual venous curvature may promote AVF maturation and better patency of vascular access. Such outcomes imply that any vascular geometry incapable of gradual adaptation to changes in flow direction is likely to incite high levels of flow disturbance. Also, acute-angled structures are apt to generate vortex flow formations, largely manifested as highly disturbed patterns within two transverse vortices. The latter lead to a complex WSS constellation, promoting intimal hyperplasia and AVF stenosis [51]. As mentioned earlier, Lee et al. [23] have established that obtuse anastomotic angles significantly reduce WSS and further promote AVF maturation, based on retrospective clinical analyses using CFD methods.

To conclude, CFD has shown promise as research methodology. Most CFD studies support the assertion that intermediate angles may be more favorable in this setting, although a few studies have differing views. Because AVF stenosis is always localized, it is speculated that its development is at least partly due to a locally altered microhemodynamic environment in the surgical aftermath. With respect to blood flow velocity, the upsurge in intravenous blood flow rate after AVF increases endothelial cell WSS, endothelial cell proliferation, and extracellular matrix deposition, thus resulting in an enlarged vascular lumen that ultimately returns WSS to a physiologic range. More and more studies have shown that as in atherosclerosis, instances of low WSS or WSS heightened by disturbed flow figure prominently in AVF status and evolution [52]. Such considerations have been largely ignored in the past. Increased intraluminal pressure regulates mural thickness through effects on wall tension and the response of vascular smooth muscle cells to mechanical stimulation. Hence, all measures should serve to reduce areas and distributions of low or disturbed-flow WSS as a starting point. Knowing the gap between theoretical findings and clinical practice, integration of CFD insights and clinical research may be preferential, as opposed to relying solely on CFD research methods.

### External support

The recently developed VasQ device (Laminate Medical Technologies, Tel Aviv, Israel) is an external vascular support apparatus constructed of nitinol (nickel-titanium alloy) that aids in AVF creation (Fig. 3). It consists of a stent to wrap around junctional arteries and an external mesh braid to cover initial 25-mm segments of anastomotic veins, neither component having direct contact with circulation [53]. The external support provided maintains an acute angle of ~40–50° between anastomosed artery and vein, impacting patency and blood flow rate (Table 4). The device does not interfere with intravascular blood flow, and its safety has been widely recognized [53, 54].

Reportedly, a relation between VasQ device usage and AVF maturation rates seems to exist. According to Benedetto et al., [55] patients implanted with VasQ devices registered a maturity rate of 100% at 35 days after surgery, far outpacing the control group (77%). These findings are consistent with those of Shahverdyan et al. [56, 57]; and Chemla et al. [53] have shown an AVF maturity benefit in patients with VasQ-assisted (vs. standard) AVFs, not to mention a lower incidence of associated complications. Leonardi et al. [58] have linked VasQ device usage to AVF maturation short-term (<1 year). In addition, 3 years outcomes of RCAVFs of Shahverdyan et al. [59] confirmed that VasQ occluders seemed to contribute to increasing the generation of functional RCAVFs.

VasQ devices provide patients with more stable arteriovenous geometries. For instance, Bozzetto et al. [60] have proven that angles between arteries and veins remain almost constant, while charting more constant flow patterns in three test subjects (vs. three controls) through postsurgical magnetic resonance imaging (MRI) and CFD studies. There were two complications (venous dilation, 1; stenosis, 1) in the control group only. Overall, VasQ devices do appear to facilitate postoperative AVF patency. A recent retrospective study by Dillavou et al. [54] has illustrated that early placement of VasQ stents may substantially improve postoperative patency, a benefit corroborated by a number of other studies [53, 56, 60]. What's more, the data generated by Palumbo et al. [61] and Benedetto et al. [55] did not reach statistical significance in terms of VasQ device patency rates, and some additional negative outcomes have surfaced as well [57, 62]. Large-scale samplings are needed to shore-up the limited data available thus far. It is noteworthy that VasQ implant locations have generally qualified as BC-AVF and RC-AVF. However, sources elsewhere have refuted the influence of implant location on study results [56, 58].

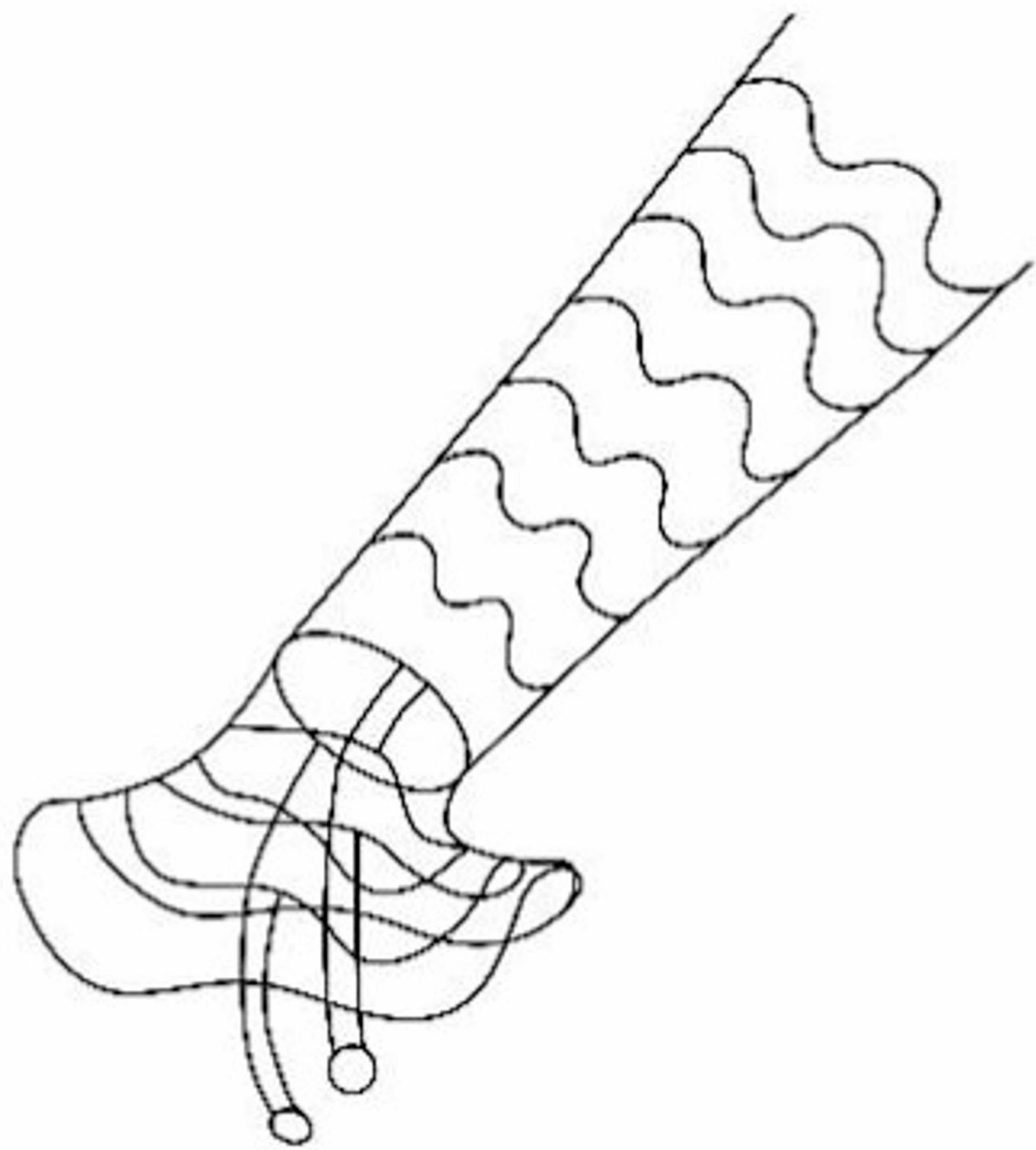

**Fig. 3** VasQ device for external AVF support

In summary, the VasQ external stent device is a promising innovation for AVF support, although its technology is considered relatively new. Large-sized research studies are essential to further explore and validate the presumptive effectiveness.

## Conclusion

This article provides a comprehensive summary of relevant research progress, highlighting the importance of anastomotic angle in AVF maturation and patency and offering insights gathered through various investigative methodologies. In clinical research, two studies support the acute angle, three studies support the intermediate angle, three studies support the obtuse angle. In CFD

**Table 4** VasQ device trials

| | Reference | Year | Patient total | Results |
|---|---|---|---|---|
| 1 | Karydis et al. | 2019 | 40 | Functional patency at 6 months (VasQ vs. controls): 100% vs. 56% |
| 2 | Benedetto et al. | 2022 | 49 | Maturity rate at 35 days (VasQ vs. controls): 96% vs. 74% |
| 3 | Shahverdyan et al. | 2023 | 300 | Maturity rate at 3 years (VasQ vs. controls): 95% vs. 89% |

research, one article support the acute angle, six articles support the intermediate angle, and one article supports obtuse angles. Therefore, We support an intermediate angle of 30–70º as optimal for AVF anastomotic angles according to the existing research results. Surgeons must exercise judgment and tailor anastomotic angles accordingly, adjusting for individual patient conditions, vessel sizes and shapes, and procedural specifications. VasQ external stent devices seem to enhance the patency of AVFs by maintaining anastomotic angles and have been associated with improved clinical outcomes in patients. A greater number of case studies are warranted in this regard. The angle of AVF is important for certain phases of the vascular access life cycle, including maturation (determining flow and outward remodeling) and maintenance (determining intimal hyperplasia and juxta-anastomotic stenosis). Hence, the distinction between early maturation and later vascular access dysfunction should receive more attention.

**Acknowledgements**
This manuscript has been copyedited at BioMed Proofreading LLC by native English speakers with pertinent biomedical expertise.

**Author contributions**
Xinyang Li and Chong Liu generated the figures, with Haidi Hu formulating the research. All authors jointly drafted the manuscript.

**Funding**
This research was supported by the following organizations: (1) National Natural Science Foundation of China (82170517); (2) Basic Research Program from Department of Education of Liaoning Province (JC2019004); and (3) 345 Talent Project of Shengjing Hospital, China Medical University.

**Data availability**
No datasets were generated or analysed during the current study.

## Declarations

**Ethical approval**
This paper is a review study and does not involve this content.

**Informed consent to participate**
This paper is a review study and does not involve this content.

**Competing interests**
The authors declare no competing interests.

Received: 6 March 2025 / Accepted: 14 May 2025
Published online: 22 May 2025

**References**

1. Obrador GT, Levin A. CKD hotspots: challenges and areas of opportunity. Semin Nephrol. 2019;39(3):308–14.
2. Bylsma LC, Gage SM, Reichert H, Dahl SLM, Lawson JH. Arteriovenous fistulae for haemodialysis: A systematic review and Meta-analysis of efficacy and safety outcomes. Eur J Vasc Endovasc Surg. 2017;54(4):513–22.
3. Zhang L, Wang F, Wang L, Wang W, Liu B, Liu J, et al. Prevalence of chronic kidney disease in China: a cross-sectional survey. Lancet (London England). 2012;379(9818):815–22.
4. Masengu A, Hanko J. Patient factors and haemodialysis arteriovenous fistula outcomes. J Vasc Access. 2017;18(Suppl 1):19–23.
5. Dember LM, Beck GJ, Allon M, Delmez JA, Dixon BS, Greenberg A, et al. Effect of clopidogrel on early failure of arteriovenous fistulas for hemodialysis: a randomized controlled trial. JAMA. 2008;299(18):2164–71.
6. Bashar K, Conlon PJ, Kheirelseid EA, Aherne T, Walsh SR, Leahy A. Arteriovenous fistula in dialysis patients: factors implicated in early and late AVF maturation failure. Surgeon. 2016;14(5):294–300.
7. Nelson PR, Mallios A, Randel M, Jennings WC. Percutaneous arteriovenous fistula creation. Semin Vasc Surg. 2021;34(4):195–204.
8. Huber TS. Surgeon characteristics and arteriovenous fistula maturation success. Am J Kidney Dis. 2020;75(2):151–2.
9. Huber TS, Berceli SA, Scali ST, Neal D, Anderson EM, Allon M, et al. Arteriovenous fistula maturation, functional patency, and intervention rates. JAMA Surg. 2021;156(12):1111–8.
10. Sadaghianloo N, Jean-Baptiste E, Rajhi K, François E, Declemy S, Dardik A, et al. Increased reintervention in radial-cephalic arteriovenous fistulas with anastomotic angles of less than 30 degrees. J Vasc Surg. 2015;62(6):1583–9.
11. Fiorina I, Raciti MV, Goddi A, Cantisani V, Bortolotto C, Chu S, et al. Ultrasound vector flow Imaging - could be a new tool in evaluation of arteriovenous fistulas for hemodialysis? J Vasc Access. 2017;18(4):284–9.
12. Rezapour M, Sepehri MM, Khavanin Zadeh M, Alborzi M. A new method to determine anastomosis angle configuration for arteriovenous fistula maturation. Med J Islam Repub Iran. 2018;32:62.
13. He Y, Terry CM, Nguyen C, Berceli SA, Shiu YT, Cheung AK. Serial analysis of lumen geometry and hemodynamics in human arteriovenous fistula for Hemodialysis using magnetic resonance imaging and computational fluid dynamics. J Biomech. 2013;46(1):165–9.
14. He Y, Northrup H, Le H, Cheung AK, Berceli SA, Shiu YT. Medical Image-Based computational fluid dynamics and fluid-Structure interaction analysis in vascular diseases. Front Bioeng Biotechnol. 2022;10:855791.
15. Kamada H, Nakamura M, Ota H, Higuchi S, Takase K. Blood flow analysis with computational fluid dynamics and 4D-flow MRI for vascular diseases. J Cardiol. 2022;80(5):386–96.
16. Soliveri L, Bozzetto M, Brambilla P, Caroli A, Remuzzi A. Hemodynamics in AVF over time: A protective role of vascular remodeling toward flow stabilization. Int J Artif Organs. 2023;46(10–11):547–54:3913988231191960.
17. Bozzetto M, Brambilla P, Rota S, Ene-Iordache B, Sironi S, Remuzzi G, et al. Toward longitudinal studies of hemodynamically induced vessel wall remodeling. Int J Artif Organs. 2018;41(11):714–22.
18. Yang CY, Li MC, Lan CW, Lee WJ, Lee CJ, Wu CH, et al. The anastomotic angle of Hemodialysis arteriovenous fistula is associated with flow disturbance at the venous stenosis location on angiography. Front Bioeng Biotechnol. 2020;8:846.
19. Galić G, Kvesić A, Tomić M, Rebac Z, Brekalo Z, Martinović V, et al. The advantages of end-to-side arteriovenous anastomosis over the other two types of arteriovenous anastomosis in dialysis patients. Coll Antropol. 2008;32(1):109–14.
20. Schmidli J, Widmer MK, Basile C, de Donato G, Gallieni M, Gibbons CP et al. Editor's Choice 2018 Vascular access: 2018 clinical practice guidelines of the European society for vascular surgery (ESVS). Eur J Vasc Endovasc Surg 55 6 757–818.
21. Xu W, Lu G, Tang W, Gong L, Lu J. Comparison of different anastomosis angles in radiocephalic fistula with modified functional end-to-side anastomosis. Int Urol Nephrol. 2023;55(12):3237–43.
22. Sivanesan S, How TV, Bakran A. Sites of stenosis in AV fistulae for haemodialysis access. Nephrol Dial Transpl. 1999;14(1):118–20.
23. Lee J, Kim S, Kim SM, Song R, Kim HK, Park JS, et al. Assessing radiocephalic wrist arteriovenous fistulas of obtuse anastomosis using computational fluid dynamics and clinical application. J Vasc Access. 2016;17(6):512–20.
24. He Y, Northrup H, Roy-Chaudhury P, Cheung AK, Berceli SA, Shiu YT. Analyses of Hemodialysis arteriovenous fistula geometric configuration and its associations with maturation and reintervention. J Vasc Surg. 2021;73(5):1778–e861.

25. Shenoy S. Surgical technique determines the outcome of the Brescia/Cimino AVF. J Vasc Access. 2017;18(Suppl 1):1–4.
26. Bharat A, Jaenicke M, Shenoy S. A novel technique of vascular anastomosis to prevent juxta-anastomotic stenosis following arteriovenous fistula creation. J Vasc Surg. 2012;55(1):274–80.
27. Darcy M, Vachharajani N, Zhang T, Mani N, Kim SK, Matson S, et al. Long-term outcome of upper extremity arteriovenous fistula using pSLOT: single-center longitudinal follow-up using a protocol-based approach. J Vasc Access. 2017;18(6):515–21.
28. LoBue A, Heuser SK, Lindemann M, Li J, Rahman M, Kelm M et al. Red blood cell endothelial nitric oxide synthase: A major player in regulating cardiovascular health. Br J Pharmacol. 2023.
29. Münzel T, Daiber A. Vascular redox signaling, endothelial nitric oxide synthase uncoupling, and endothelial dysfunction in the setting of transportation noise exposure or chronic treatment with organic nitrates. Antioxid Redox Signal. 2023;38(13–15):1001–21.
30. Kudze T, Ono S, Fereydooni A, Gonzalez L, Isaji T, Hu H, et al. Altered hemodynamics during arteriovenous fistula remodeling leads to reduced fistula patency in female mice. JVS Vasc Sci. 2020;1:42–56.
31. Huang J, Cai C, Zheng T, Wu X, Wang D, Zhang K, et al. Endothelial scaffolding protein ENH (Enigma homolog protein) promotes PHLPP2 (Pleckstrin homology domain and Leucine-Rich repeat protein phosphatase 2)-Mediated dephosphorylation of AKT1 and eNOS (Endothelial NO Synthase) promoting vascular remodeling. Arterioscler Thromb Vasc Biol. 2020;40(7):1705–21.
32. An L, Shen Y, Chopp M, Zacharek A, Venkat P, Chen Z, et al. Deficiency of endothelial nitric oxide synthase (eNOS) exacerbates brain damage and cognitive deficit in A mouse model of vascular dementia. Aging Dis. 2021;12(3):732–46.
33. Gauer S, Balint B, Kollmann C, Federspiel JM, Henn D, Bandner-Risch D, et al. Dysregulation of endothelial nitric oxide synthase does not depend on hemodynamic alterations in bicuspid aortic valve aortopathy. J Am Heart Assoc. 2020;9(18):e016471.
34. Bai H, Wei S, Xie B, Wang Z, Li M, Qiao Z, et al. Endothelial nitric oxide synthase (eNOS) mediates neointimal thickness in arteriovenous fistulae with different anastomotic angles in rats. J Vasc Access. 2022;23(3):403–11.
35. Falzon I, Northrup H, Guo L, Totenhagen J, Lee T, Shiu YT. The geometry of arteriovenous fistulas using endothelial nitric oxide synthase mouse models. Kidney360. 2020;1(9):925–35.
36. Northrup H, Somarathna M, Corless S, Falzon I, Totenhagen J, Lee T, et al. Analysis of geometric and hemodynamic profiles in rat arteriovenous fistula following PDE5A Inhibition. Front Bioeng Biotechnol. 2021;9:779043.
37. Samady H, Jaber W. Harnessing vascular biology and fluid dynamics to risk stratify patients with acute coronary syndromes. JACC Cardiovasc Interv. 2022;15(20):2049–51.
38. Ishida F, Tsuji M, Tanioka S, Tanaka K, Yoshimura S, Suzuki H. Computational fluid dynamics for cerebral aneurysms in clinical settings. Acta Neurochir Suppl. 2021;132:27–32.
39. Fulker D, Ene-Iordache B, Barber T. High-Resolution computational fluid dynamic simulation of haemodialysis cannulation in a Patient-Specific arteriovenous fistula. J Biomech Eng. 2018;140(3).
40. Krampf J, Agarwal R, Shenoy S. Contribution of inflow artery to observed flow in a vascular access: A computational fluid dynamic modeling study of an arteriovenous fistula circuit. J Vasc Access. 2021;22(3):417–23.
41. Remuzzi A, Bozzetto M, Brambilla P. Is shear stress the key factor for AVF maturation? J Vasc Access. 2017;18(Suppl 1):10–4.
42. Lancellotti RM, Vergara C, Valdettaro L, Bose S, Quarteroni A. Large eddy simulations for blood dynamics in realistic stenotic carotids. Int J Numer Method Biomed Eng. 2017;33(11).
43. Prouse G, Stella S, Vergara C, Quarteroni A, Engelberger S, Canevascini R, et al. Computational analysis of turbulent hemodynamics in radiocephalic arteriovenous fistulas to determine the best anastomotic angles. Ann Vasc Surg. 2020;68:451–9.
44. Stella S, Vergara C, Giovannacci L, Quarteroni A, Prouse G. Assessing the disturbed flow and the transition to turbulence in the arteriovenous fistula. J Biomech Eng. 2019;141(10).
45. Cunnane CV, Cunnane EM, Moran DT, Walsh MT. The presence of helical flow can suppress areas of disturbed shear in parameterised models of an arteriovenous fistula. Int J Numer Method Biomed Eng. 2019;35(12):e3259.
46. Ene-Iordache B, Cattaneo L, Dubini G, Remuzzi A. Effect of anastomosis angle on the localization of disturbed flow in 'side-to-end' fistulae for haemodialysis access. Nephrol Dial Transpl. 2013;28(4):997–1005.
47. Van Canneyt K, Pourchez T, Eloot S, Guillame C, Bonnet A, Segers P, et al. Hemodynamic impact of anastomosis size and angle in side-to-end arteriovenous fistulae: a computer analysis. J Vasc Access. 2010;11(1):52–8.
48. Hull JE, Balakin BV, Kellerman BM, Wrolstad DK. Computational fluid dynamic evaluation of the side-to-side anastomosis for arteriovenous fistula. J Vasc Surg. 2013;58(1):187–e931.
49. Silva JdA, Karam-Filho J, Borges CCH. Computational analysis of anastomotic angles by blood flow conditions in Side-to-End Radio-Cephalic fistulae used in Hemodialysis. J Biomedical Sci Eng. 2015;08(3):131–41.
50. Carroll J, Varcoe RL, Barber T, Simmons A. Reduction in anastomotic flow disturbance within a modified end-to-side arteriovenous fistula configuration: results of a computational flow dynamic model. Nephrol (Carlton). 2019;24(2):245–51.
51. Rajabi-Jagahrgh E, Krishnamoorthy MK, Wang Y, Choe A, Roy-Chaudhury P, Banerjee RK. Influence of Temporal variation in wall shear stress on intima-media thickening in arteriovenous fistulae. Semin Dial. 2013;26(4):511–9.
52. Browne LD, Bashar K, Griffin P, Kavanagh EG, Walsh SR, Walsh MT. The role of shear stress in arteriovenous fistula maturation and failure: A systematic review. PLoS ONE. 2015;10(12):e0145795.
53. Chemla E, Velazquez CC, D'Abate F, Ramachandran V, Maytham G. Arteriovenous fistula construction with the VasQ™ external support device: a pilot study. J Vasc Access. 2016;17(3):243–8.
54. Dillavou ED, Lucas JF, Woodside K, Burgess J, Farber A, Hentschel D, et al. VasQ U.S. Pivotal study demonstrates the safety and effectiveness of an external vascular support for arteriovenous fistula creation. J Vasc Surg. 2023;78(5):1302–e123.
55. Benedetto F, Spinelli D, Derone G, Cutrupi A, Barillà D, Pipitò N. Initial single-center experience with a new external support device for the creation of the forearm native arteriovenous fistula for Hemodialysis. J Vasc Access. 2022;23(4):524–31.
56. Shahverdyan R, Tabbi P, Mestres G. Multicenter European real-world utilization of VasQ anastomotic external support device for arteriovenous fistulae. J Vasc Surg. 2022;75(1):248–54.
57. Shahverdyan R, Meyer T, Matoussevitch V. Patency and functionality of radiocephalic arteriovenous fistulas with an external support device (VasQ™): Real-world single-center experience. J Vasc Access. 2021;22(2):166–72.
58. Leonardi G, Campagna M, Pellicanò V, Guarena C, Bergamo D, Lavacca A, et al. Implanted blood vessel external support device (VasQ™) for creation of Hemodialysis arteriovenous fistula: A single-center experience. J Vasc Access. 2021;22(4):658–65.
59. Shahverdyan R, Hentschel DM. Achieving high maturation and cannulation rates of radial-cephalic arteriovenous fistulas with VasQ™ device. Semin Dial. 2023;36(2):147–54.
60. Bozzetto M, Soliveri L, Poloni S, Brambilla P, Curtò D, Condemi GC et al. Arteriovenous fistula creation with VasQ(TM) device: A feasibility study to reveal hemodynamic implications. J Vasc Access. 2022:11297298221087160.
61. Palumbo R, Dominijanni S, Centi A, D'Urso G, Tatangelo P, Floccari F, et al. Hemodynamic impact of VASQ device in vascular access creation. J Vasc Access. 2022;23(1):105–8.
62. Karydis N, Bevis P, Beckitt T, Silverberg D, Halak M, Calder F. An implanted blood vessel support device for arteriovenous fistulas: A randomized controlled trial. Am J Kidney Dis. 2020;75(1):45–53.


## Publisher's note