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Application Progress of Point-of-Care Ultrasound for Cannulation in Hemodialysis Patients with Difficult Arteriovenous Fistulae

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Abstract: The occurrence of difficult arteriovenous fistulas makes the use of vascular access in hemodialysis patients face great challenges. With the widespread application of point-of-care ultrasound, POCUS technology, it provides a new solution for clinical practice. This article reviews the principle, basic process, application status, current clinical challenges and development direction of difficult arteriovenous fistulas cannulation guided by POCUS technology, in order to provide reference for the standardized clinical application and future research direction of this technology.

Keywords: Point-of-care ultrasound technology; Arteriovenous fistula; Hemodialysis nursing; Summary

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1. Introduction

End-stage renal disease, ESRD has become a global public health problem. At present, there are more than 3 million patients with ESRD in China, and the number of patients continues to increase [1]. Maintenance hemodialysis, MHD is one of the most commonly used renal replacement therapies for ESRD. Studies show that China's dialysis population is gradually growing and is expected to reach 870,000 by 2025 [2]. High-quality dialysis treatment is the basis for ensuring the long-term survival of patients, and some patients can achieve a survival period of more than 10–20 years [3]. Arteriovenous fistula, AVF has become the preferred non-physiological vascular access for MHD patients due to the advantages of hemodynamic stability, convenient use and high safety [4]. However, clinically, some arteriovenous fistulas are called difficult arteriovenous fistulas because of their high cannulation difficulty [5–8]. This mainly includes three types of situations:

(1) Suboptimal vascular characteristics

Such as the diameter of the vessel is too small (< 5 mm), the depth from the skin surface is too large (> 6

mm), the segment available for cannulation is short (< 10 cm), the running is tortuous or the position is too deep, the vessel wall is brittle, and it is easy to slide.

(2) Compromised functional status

Such as insufficient access blood flow (< 500 mL/min), poor maturation, or complications such as thrombosis, stenosis, and calcification;

(3) Difficulties in clinical use

Such as newly formed early-stage arteriovenous fistulas, high-position arteriovenous fistula, or vessels that rely on ultrasound guidance due to repeated cannulation failure (defined as ≥ 3 failures in 4 consecutive dialysis sessions in the near future).

The traditional method of arteriovenous fistula cannulation is blind cannulation technique, but the application of this method for difficult arteriovenous fistulas will reduce the success rate of cannulation, and repeated cannulation failure can lead to serious complications such as hematoma, infection and pseudoaneurysm, which can easily lead to the loss of arteriovenous fistula [9]. In recent years, POCUS has gradually become an important means for cannulating difficult AVF because of its simplicity, visualization, rapidity and high repeatability. Many studies have confirmed [11]that using POCUS to assist in cannulating difficult arteriovenous fistulas can not only significantly improve the cannulation success rate of AVF, but also effectively prolong the service life of AVF [10–12]. Therefore, the purpose of this article is to summarize the principle and basic process of POCUS-guided cannulation for difficult AVF, explore the current application status of POCUS in cannulation of MHD patients with difficult AVF, and analyze the challenges faced in its clinical operation, so as to provide practical guidance for optimizing the vascular access cannulation strategy of MHD patients.

2. The principle of POCUS in cannulating difficult AVF

Ultrasound technology began to be applied in the medical field in 1950s, aiming to assist the diagnosis and treatment of diseases through non-invasive, real-time, and high-resolution imaging of the internal body [13]. This technique began to be applied in nephrology in the 1990s [14]. As an important extension in clinical practice, POCUS can break through the space and time limitations of traditional ultrasound equipment by virtue of its portability, enabling medical staff to quickly obtain real-time image information at the patient's bedside [15]. In recent years, POCUS has been applied to the preoperative evaluation, intraoperative and postoperative detection and follow-up, and guided cannulation of AVF in MHD patients [16,17]. POCUS has important clinical application value in guiding the cannulation for difficult AVF because of its portability and visual puncture. Its core technology lies in transforming the cannulation process from the blind technique that relies on subjective experience into objective, image-based clinical procedure. First of all, conduct a comprehensive pre-cannulation visual evaluation, accurately measure the effective vessel lumen diameter and depth from the skin surface, and clearly identify vascular pathologies that cannot be detected by traditional palpation, such as stenosis, thrombus and calcification, so as to provide decision-making basis for selecting the best puncture site; Then, the needle tip is dynamically guided in real time during the cannulation process to ensure that the needle's trajectory is still clearly visible in complex situations such as aberrant vessel courses or scar tissue; Finally, after successful cannulation, the accurate position of the needle tip in the vascular lumen can be confirmed immediately and the blood flow patency can be evaluated, providing immediate imaging confirmation for subsequent treatment [18–20]. Therefore, this technology reduces the difficulty of cannulating difficult AVF by transforming the cannulation of difficult arteriovenous

fistulas from a blind procedure into an accurate visual one, and can significantly improve the cannulation success rate. It is a key technical means to achieve long-term vascular access maintenance in MHD patients.

3. The basic process of POCUS in difficult AVF cannulation

At present, the process of POCUS-guided cannulation of difficult AVF is roughly divided into three steps [21–24].

(1) Step 1

Before cannulation, physical examination and evaluation of AVF such as inspection, palpation, and auscultation are carried out, and then the vessel course, branching pattern, inner diameter, depth from the skin, wall thickness and hemodynamic status are evaluated by ultrasonographic assessment, so as to avoid vascular abnormalities or pathologies such as stenosis and tortuosity, and determine the best puncture site and mark it;

(2) Step 2

During cannulation, disinfect the skin, spread the towel, put the sterile protective sheath on the ultrasound probe and apply the sterile coupling gel. The operator displays the target vessel at the center of the screen, and then guides it in real time with the transverse section or longitudinal section, inserts the needle at the center of the probe while looking at the ultrasound screen, and dynamically adjusts the puncture angle and depth to a suitable position;

(3) Step 3

After successful cannulation, fix the puncture needle, and review the needle placement and vascular status by ultrasound to ensure that there are no abnormalities.

4. Current application of POCUS in AVF cannulation

4.1. Cannulation success rate

A single successful cannulation of an AVF refers to achieving venipuncture without repeated attempts, vessel perforation, or missing the target vessel in one procedure [24]. A successful first attempt can reduce the incidence of hematoma, vascular injury, and scarring. By providing real-time visualization during cannulation, POCUS optimizes vascular assessment and puncture-site selection, and has become a key technique for improving the first-attempt success rate in difficult AVF. Numerous studies from different perspectives have verified its effectiveness. In a randomized controlled study, Jin Juan et al. reported that vessels in first-time AVF cannulation patients were fragile and under high pressure [25]. By using POCUS to assess vessel diameter and trajectory and to identify the optimal puncture site and needle entry approach, the observation group showed a significantly higher first-attempt success rate than the control group ($p < 0.05$), along with reduced hematoma and thrombosis related to cannulation failure. Liu Hua et al. also confirmed these findings: using handheld POCUS to examine vessel morphology, depth, and course and to avoid stenosis or hematoma sites, the first-attempt success rate in the ultrasound group reached 86.7%, compared with only 63.3% using the traditional method [26]. Moreover, the study by Cheng Ying et al. highlighted a collaborative physician-nurse model, in which physicians first performed POCUS evaluation and site marking and nurses executed real-time guided cannulation [27]. Under this model, the first-attempt success rate reached 100.0%, markedly higher than the control group's 92.1%. Collectively, these findings demonstrate the ability of POCUS to improve both the objective success and safety of cannulation procedures. Nevertheless,

the magnitude of improvement varies across studies, likely due to differences in patients' vascular conditions, ultrasound equipment performance, operator proficiency, and team collaboration. Therefore, future research should establish standardized operating procedures, systematically evaluate the effectiveness of training programs on cannulation proficiency, and validate optimal strategies in larger and more diverse patient populations, thereby providing robust evidence for broader clinical application.

4.2. Pain reduction

For MHD patients, cannulation-related pain is a long-standing challenge that affects treatment experience and adherence [28]. In difficult AVF cannulations, the increased procedural complexity and repeated failed attempts can exacerbate mechanical tissue injury and trigger patient stress responses, thereby intensifying pain perception. POCUS-guided reduction of unsuccessful attempts is essential for minimizing pain. Wen Fen et al. used a numerical rating scale to assess pain in patients undergoing POCUS-guided cannulation for difficult AVF and found significantly lower pain scores in the observation group than in the traditional blind puncture group ($p < 0.05$) [29]. Liu Wenjie et al. reported that clarifying needle entry path and depth with POCUS before the procedure avoided repeated contact of the needle tip with the vessel wall, reduced pain perception, and improved patient tolerance [30]. A randomized controlled trial by Zhang Pei et al. further confirmed that ultrasound guidance not only reduces pain but also enhances overall comfort and treatment adherence in MHD patients, exerting positive effects on both physical and psychological well-being [31]. Although the above studies yielded consistent results, pain-assessment tools differed among researchers. Moreover, pain is a subjective experience strongly influenced by psychological status, prior cannulation experiences, and cultural background, variables often insufficiently controlled in existing studies. Thus, future studies should adopt standardized pain-assessment protocols and more rigorously control potential confounders to generate more reliable evidence regarding the effectiveness of POCUS in improving cannulation-related patient experience.

4.3. Cannulation-related vascular complications

Because MHD patients undergo repeated vascular access cannulations over time, they are prone to thrombosis, stenosis, bleeding, hematoma, pseudoaneurysm, and infection [32]. In difficult AVF cannulations, repeated attempts due to procedural challenges markedly increase these risks. Therefore, using POCUS to determine vascular anatomy and functional status before cannulation is essential for preventing complications. Xiong Caixia et al. reported significantly lower rates of hematoma and thrombosis in the POCUS-guided group than in the blind puncture group, with zero occurrences of aneurysm or infection, indicating that ultrasound guidance effectively mitigates complication risks [33]. Zhang Fan et al. further demonstrated that POCUS-guided cannulation significantly reduces the incidence of subcutaneous hematoma, induration, oozing, and vascular injury [34]. Similarly, the study by WU et al. confirmed significantly lower rates of early complications (such as subcutaneous hematoma and oozing) in the POCUS group compared with the control group [35]. In addition, preliminary evidence suggests potential long-term benefits. Wang Chunhua and colleagues conducted a 1-year follow-up and found that 96.7% of patients in the ultrasound-guided group remained free of complications (only 1 case of stenosis), significantly higher than the 53.3% in the control group; stenosis, sclerosis, and aneurysmal dilatation were notably more frequent in the control group ($p < 0.05$) [36]. Overall, current evidence consistently indicates the substantial advantage of POCUS in reducing cannulation-related complications in difficult AVF, especially early complications. Although preliminary long-term data are promising, high-quality long-term evidence remains limited. Future research should adopt larger sample sizes, more rigorous

designs, and extended follow-up periods to comprehensively evaluate the long-term value of POCUS in protecting vascular access and prolonging AVF lifespan.

4.4. Cannulation time

Current evidence shows that POCUS-guided cannulation of difficult AVF may prolong procedure time. Liu Wenjie et al. reported that due to the need for more refined vascular assessment and path localization, the total operation time was longer in the POCUS group than in the blind puncture group [30]. Similarly, in a randomized controlled trial involving 32 early AVF patients, Kumbar found that the additional visualization steps led to longer assessment and cannulation times [37]. However, some studies found no significant difference or even improved overall efficiency in specific difficult scenarios. Chen S et al. showed that pre-procedure assessment time and cannulation time (defined as the time from draping to successful insertion of the second needle) were similar between groups, suggesting that convenient equipment and operator confidence may narrow time differences [38]. Eves J et al. defined cannulation time as the period from first skin puncture to successful flushing of the second needle, and reported that although POCUS did not shorten procedure time, it progressively reduced the time gap between groups when cannulating difficult AVF, improving overall efficiency. The heterogeneity of conclusions is notable [39]. First, studies differ in defining start and end points of timing, making direct comparison difficult. Second, operator experience plays a major role: novice users often require more time, while experienced practitioners may achieve equal or greater efficiency. Future studies should unify measurement standards for cannulation time and adopt more rigorous designs—including accounting for operator experience, to accurately assess the true impact of POCUS on procedure duration in difficult AVF cannulation.

5. Challenges and prospects of POCUS in difficult AVF punctures

5.1. Establish a standardized and process-oriented training and assessment for nurse-led Point-of-Care Ultrasound (POCUS)

With the widespread application of POCUS in difficult AVF punctures, the role of nurses should be transformed from traditional operators to clinical practitioners capable of integrating assessment, decision-making, and operation. This places high demands on nurses' comprehensive operational competence. The current global training systems that complement it, however, has lagged behind in development. Research by Knutse K in Norway indicates that standardized training is a necessary prerequisite for enabling medical personnel to master this technology [40]. However, there are significant variations in nurses' abilities to interpret ultrasound images and perform puncture procedures, owing to their training system remains inadequate. What is worth to notice that there is currently a domestic lack of standardized procedures for this operation, which has to some extent limited the promotion and application of this technology in China. Therefore, it is recommended that Chinese medical personnel draw upon existing POCUS operational protocols as a foundation, develop standardized procedures for nurse-led POCUS guided AVF puncture for patients with MHD. It can cover theoretical knowledge learning, simulated operation training and assessment evaluation these three core elements, with contents focus on vascular assessment, pathway selection, and dynamic guidance and other technologies. Through this approach of integrating theory with practice, nurses are certified to ensure they possess the ability to perform independently and in accordance with established standards [41]. Consequently, through this standardized training pathway and

corresponding assessment mechanism, not only enables the rapid and standardized training of qualified POCUS operating nurses, but also lay a solid foundation for their clinical reasoning and ability to solve complex problems, providing a talent pool to ensure the standardized promotion of this technology.

5.2. Balancing and integrating standardization and individualization in POCUS procedures

There remains a lack of standardized procedures for POCUS guided puncture techniques in clinical practice and research, and demonstrates the exploration and integration of standardization and individualization across multiple levels. Regarding guidance methods, scholars in China including Wu Aichun et al. found that ultrasound-guided longitudinal section imaging offers advantages in improving puncture success rates, enhancing patient satisfaction, and reducing complications in 40 obese MHD patients which possesses advantages [42]. An international survey on the use of POCUS guided AVF puncture concluded that the combined transverse-longitudinal approach is most commonly used, followed by the transverse section, while the longitudinal section is relatively less frequently employed [43]. The most commonly used method is the combined transverse and longitudinal approach, followed by the transverse section, while the longitudinal section is relatively less frequently employed, which was investigate by international survey on the use of POCUS guided AVF puncture. This suggests potential variations in patient-specific operational practices, vascular assessment criteria, and clinical training priorities among medical teams. So, in the future, we should integrate the practical experience and research data from different medical institutions to establish a standardized operating procedure. With regard to the use of ultrasound probes, Wen fen et al. recommends increasing vascular filling by appropriately occluding the proximal end of the fistula vessels to achieve a clearer vascular field of view [29]. Zhan Yuemeiet al. also proposed a similar viewpoint, emphasizing the importance of controlling probe pressure for precise puncture [44]. Nevertheless, Zhang Fanet al. emphasized avoiding excessive tightness or pressure from the probe against the skin to prevent compression of blood vessels, which could compromise the effectiveness of the puncture [34]. The differing viewpoints of the above researchers reflect when during the procedure, dynamic adjustments should be made based on vascular conditions, the patient's specific circumstances, and the characteristics of the probe. Moderate pressure facilitates visualization. Yet excessive pressure may prove counterproductive. Therefore, operators should dynamically assess conditions during procedures to find the optimal balance between probe pressure and vascular filling, thereby achieving the best imaging and puncture outcomes. Huang Yaling et al. emphasizes the importance of clinical experience and advocates flexible selection of the three common AVF puncture techniques based on vascular conditions [45]. Meanwhile, Liu Wenjie et al. proposed an AVF puncture localization naming system based on POCUS assessment, using letter-number combinations to mark puncture angles and directions to enhance puncture accuracy [30]. Therefore, in establishing standardized processes, it is essential to provide operators with a clear framework to follow while also encouraging them to adapt flexibly based on actual circumstances. This approach ultimately achieves individualized precision operations guided by standardization.

5.3. Establish a system for assigning puncture levels and matching the difficulty of complex AVF

Good Vascular Access is the prerequisite for the nursing staff successfully performing puncture. The proficiency level of nursing staff in performing punctures is a crucial safeguard for Successfully AVF puncturing, reducing puncture injury and complications. According to existing guidelines, it is explicitly recommended that complex internal fistulas should be punctured by experienced nurses [46]. However, clinical practice generally lacks of a set of objective criteria to match nursing capabilities with the complexity of AVF, which leads to uncertainty in

the success rate of the operation. Therefore, to enhance the precision management of arteriovenous fistulas, it is recommended to establish a tiered system for puncture practitioners and a difficulty-matching protocol for complex arteriovenous fistulas. It has been confirmed in Canada that through rigorous assessment criteria, nursing competencies are categorized into low, medium, and high levels [47]. Nurses with advanced competency can accurately assess and successfully perform punctures on various complex AVF. And domestic scholars including Xiao Guanghui et al. have developed a nurse-level authorization system that incorporates POCUS proficiency as a core criterion [48]. They demonstrated that complex fistula cannulation performed by certified advanced-practice nurses significantly boosts the success rate of safe cannulation, mitigates complications, and elevates the patient's clinical experience. Hence the future research should prioritize the development and validation of an assessment system for nurses' puncture proficiency and a difficulty grading tool for complex AVF that will provide core support for establishing a scientifically sound and standardized "operator-fistula matching" system, thereby enhancing the success rate and safety of puncturing complex AVF.

5.4. Sterile management and optimization of POCUS

As an invasive procedure, sterile technique management of AVF puncture is critical for preventing bloodstream infections associated with vascular access. Although POCUS reduces mechanical injury by minimizing repeated needle punctures, but his guidance process itself also increases the risk of new infections. Evidence suggests that improper management of ultrasound probes, coupling agents, and operational procedures may induce cross-infection during ultrasound-guided puncture [49]. Therefore, strengthening aseptic management of ultrasound-guided techniques is crucial for reducing the incidence of infection. International guidelines recommend ultrasound-guided QVF aspiration to use sterile coupling agent during operation, equip the probe with a sterile protective cover, and disinfect the probe with sterile wipes after use [50]. According to the Chinese expert consensus on ultrasound use, T-Spray Wipes (Contains quaternary ammonium salts) are the more suitable ultrasonic probe disinfecting wipes [51]. The above measures collectively provide a reference framework for the fundamental operational procedures aimed at preventing infection and ensuring safety. However, in clinical practice, aseptic technique still faces challenges, particularly in the use of coupling agents. On the one hand, Traditional large-bottle coupling agents are difficult to maintain in a sterile state during repeated use; on the other hand, even when using sterile coupling agents, there remains a potential risk during the puncture procedure that the agent could be introduced into subcutaneous tissue or even blood vessels via the needle tip. The long-term biological effects of this on the human body are not yet fully understood, which further research is urgently needed [52]. Owing to this, future efforts should focus on the entire sterile management process for POCUS guided punctures. While further optimizing standardized sterile procedures, innovation in related technologies and products should be encouraged. This includes developing sterile coupling agents, improving probe disinfection protocols, and creating integrated sterile guidance devices to fundamentally eliminate infection risks.

6. Summary

POCUS provides a new direction for cannulating difficult AVF in MHD patients through visual evaluation and precise positioning, especially in improving the cannulating success rate, reducing pain and reducing short-term procedure-related complications. However, at present, there is a lack of a unified standardized system from technical operation, personnel training, management matching to aseptic protocols, which affects the application

and promotion of POCUS in difficult AVF cannulation in MHD patients. In view of this, future research should focus on the formulation of various standardized tools and protocols, and on this basis, through the design of rigorous large sample, multi-center randomized controlled trials to verify its important value in improving the long-term patency rate of arteriovenous fistula and reducing long-term complications, so as to lay a solid evidence-based foundation for the safe, efficient and standardized clinical application of this technology.

Disclosure statement

The authors declare no conflict of interest.

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