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Advances on ultrasound-guided radial artery catheterization

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Highlights

- Ultrasound-guided radial artery catheterization can effectively improve the success rate of first-time puncture and reduce the total puncture time and the incidence of complications.
- Ultrasound-guided radial artery catheterization methods should be selected based on the specific characteristics of individual patients.

Abstract

A higher success rate in ultrasound-guided radial artery catheterization has been demonstrated by numerous studies when comparing to traditional puncture catheterization, because it significantly shortens the overall puncture time and reduces the incidence of related complications. This review summarizes the methods, influencing factors, related complications and clinical application of ultrasound-guided radial artery catheterization in the perioperative period.

Keywords: Ultrasound-guided radial artery puncture, catheterization, complications, influencing factors, research progress

Introduction

Arterial puncture catheterization is an invasive procedure that involves puncturing and catheterizing the major arteries in the limbs of the human body. It is commonly used in clinical practice to dynamically monitor vital signs, such as blood pressure changes, and perform blood gas analysis to provide guidance for clinical treatment accordingly. The radial artery is often preferred as the first choice for arterial puncture in clinical practice due to its shallow location, obvious pulsation, absence of accompanying veins and rich collateral circulation. Because of less limb exposure, puncture at radial artery usually has lower incidence of post-puncture complications and facilitates better postoperative recovery. However, traditional radial artery puncture catheterization, i.e., palpation guided puncture, mainly relies on the surgeon's experience, with an unstable puncture efficacy. Additionally, owing to the diversity and complexity of clinical patients, such as pediatric patients, shock patients, obese patients, and critically ill patients, puncture failures are often encountered. Ultrasound (US)-guided radial artery puncture and catheterization, as a new type of puncture method, can effectively improve the success rate of first-time puncture and shorten the total puncture time, with a lower incidence of complications [1, 2]. Research has shown that US-guided puncture and catheterization has little effect on the distal blood flow of the puncture site, with minimal damage and faster recovery of the radial artery. Distal radial artery puncture can also reduce radial artery occlusion in the wrist and prevent other complications [3]. Furthermore, US-guided radial artery puncture and catheterization has shown significant advantages in standardizing training for resident doctors [4]. This review comprehensively describes the methods, influencing factors, related complications and clinical applications of US-guided radial artery catheterization.

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Table 1. Comparison of the advantages and disadvantages of common puncture methods

Methods	Advantages	Disadvantages
Short-axis out-of-plane method	i. Clearly determining the relative position of the puncture needle and the vessel lumen ii. Short puncture time iii. Fully displaying the radial artery and adjacent tissues and structures, which is beneficial for adjusting the puncture needle iv. Higher success rate of first puncture	i. Difficult to determine the position of the needle tip ii. Easily penetrating the vessel wall iii. Difficult to operate: lacking guidance after puncturing into the vessel and requiring operator's experience
Long-axis in-plane method	i. Clear visualization of the puncture needle tip position i. Higher success rate of initial puncture compared to out-of-plane in the short axis [10] ii. More precise determination of the relative position of the puncture needle to the vessel	i. Difficulty in establishing the relative position of the puncture needle to the vessel lumen ii. Lengthy puncture times iii. Difficult to manipulate: challengingly maintaining the puncture needle, radial artery, and ultrasound beam in the same plane at all times during the operation
Short-axis out-of-plane combined with Long-axis in-plane method	i. Ensuring the needle tip remaining within the ultrasound visual field at all times ii. Shorter puncture time iii. Significant improvement in the success rate of initial puncture iv. Reduced incidence of complications	i. Time needed to become proficient in operating the ultrasound machine and precisely locating the needle [11]
Dynamic needle tip positioning method	i. Same advantages as the short-axis plane approach ii. Significantly improving the success rate of puncture catheterization iii. Clearly observing the direction of progress of the needle from penetrating the skin to entering the blood vessel iv. Helping operators determine the optimal puncture site i. Timely adjusting and re-puncturing if the initial puncture fails [12]	i. Difficult to operate: requiring the probe to be accurately moved multiple times, and the operator to practice multiple times and have certain experience ii. Repeatedly pushing the puncture needle into the artery after the puncture, which may require more time compared to other ultrasound-guided methods
Developing lines-guided localization method	i. Shortening the surgical time: both the time for puncture point positioning and the puncture time ii. Accurately and quickly locating the puncture site iii. Reducing the difficulty of hand-eye coordination iv. Improving the first puncture success rate and overall puncture success rate	i. A certain level of difficulty in requiring visual confirmation of the midpoint for puncture, and certain experience of the operator

US-guided radial artery puncture methods

Unlike traditional radial artery puncture and catheterization, US-guided radial artery puncture and catheterization initially utilizes the short-axis out-of-plane method and long-axis in-plane method. Based on the methods, many other advanced methods with increasing advantages have emerged, e.g., the short-axis out-of-plane combined with long-axis in-plane method, oblique plane method, dynamic needle tip positioning method and developing lines-guided localization method. The advantages and disadvantages of each method are shown in **Table 1**.

Short-axis out-of-plane method

When performing radial artery puncture and catheterization using the short-axis out-of-plane method, the operator first locates the radial artery by US technology to determine the appropriate puncture site. Once the puncture point is identified, the surgeon holds the US probe in left hand and adjusts it to the center of the cross-sectional image of the radial artery on the screen. Meanwhile, the right hand holds the needle and punctures the skin at an angle of 30-45° at the puncture point. If blood return is observed, the needle tail was pressed down and continued to advance at an angle of 10-15° relative to the skin. After that, the

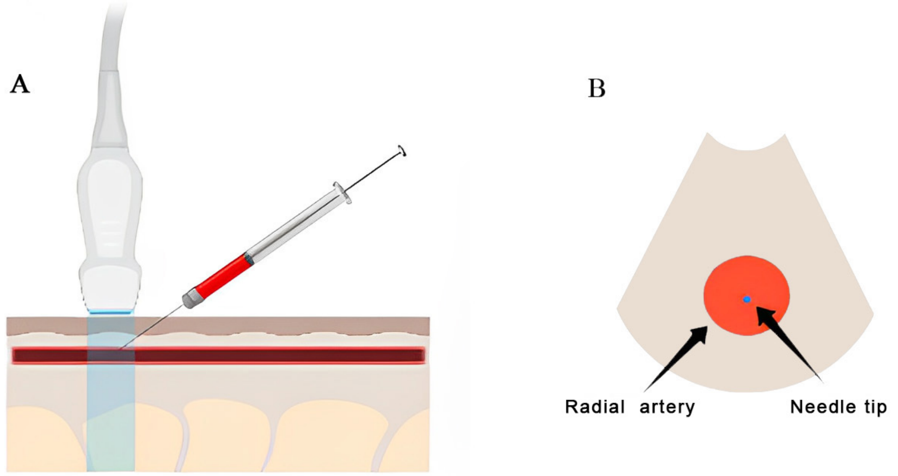

Figure 1. Schematic diagram of the short-axis out-of-plane method. (A) Position of ultrasound probe and puncture needle; (B) Schematic ultrasound image of the radial artery when the short-axis out-of-plane technique is used.

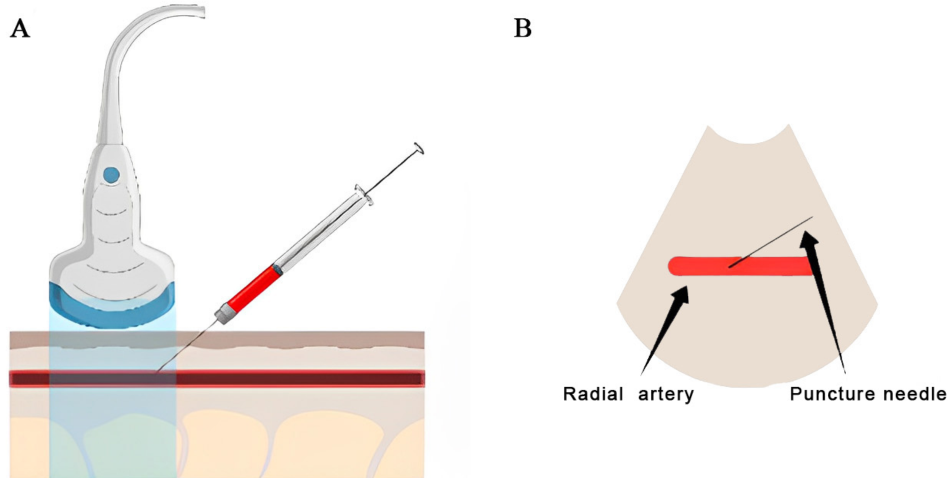

Figure 2. Schematic diagram of the long-axis in-plane method. (A) Position of the ultrasound probe and puncture needle; (B) Schematic ultrasound image of the radial artery using the long-axis in-plane technique.

needle core is slowly withdrawn, and the catheter sheath is inserted into the radial artery. If there is no blood return, the needle tail can be pressed down and continued to advance until blood flow returns to normal. Throughout the process, special attention should be paid to continuously adjusting the probe to keep the needle tip visible during the needle insertion (**Figure 1**).

Long-axis in-plane method

The long-axis in-plane method involves the operator holding the US probe with their left hand and placing it at the puncture point, with the long-axis of the probe parallel to the long-axis of the radial artery to obtain longitudinal imaging of the radial artery. The right hand of the operator holds the puncture needle, which is inserted in from the side of the US probe to make sure the direction of the needle is parallel to the blood vessel. At this point, the puncture needle can be observed on the image. When advancing the puncture needle to the lumen of the radial artery, it is important to observe for any blood return as it is difficult to ensure that the puncture needle is in the same plane as the radial artery. If there is backflow of blood, the operator can continue advancing the needle, and then insert catheter and remove the stylet. If there is no blood return, the short-axis out-of-plane method can be used for repositioning (**Figure 2**).

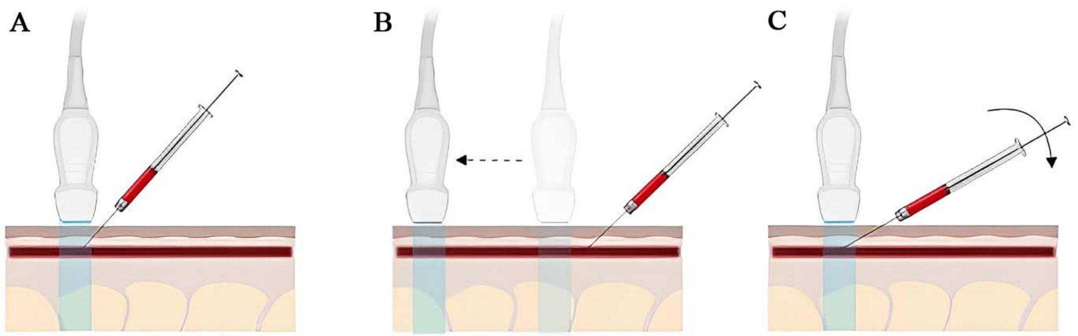

Figure 3. Schematic diagram of radial artery puncture and catheterization using the dynamic needle tip localization method. (A) Needle advancement based on the short-axis out-of-plane puncture method. (B) The ultrasound probe is moved towards the proximal end until the hyperechoic bright spot of needle tip disappears. (C) The puncture needle is further advanced until the hyperechoic bright spot of needle tip reappears on the image.

Short-axis out-of-plane combined with long-axis in-plane method

Short-axis out-of-plane combined with long-axis in-plane puncture method is generally divided into two types: "in-plane first and out-of-plane later" and "out-of-plane first and in-plane later". The first type is usually used as a remedy after the failure of the long-axis in-plane method. The operator uses the long-axis in-plane method at first. If the puncture fails or there is no blood return, the US probe is rotated 90°, and the short-axis out-of-plane method is adopted. This involves adjusting the needle tip above the short-axis of the radial artery and then proceeding with the puncture and catheter placement. The second method is more common. First, the short-axis out-of-plane method is used to measure the diameter of the radial artery and the distance between the skin, and then the long-axis in-plane method is used to determine the direction of the radial artery course to accurately locate the radial artery. Then the operator uses the long-axis in-plane method to puncture and place the catheter. Wang et al. found that compared with traditional palpation, using the short-axis out-of-plane combined with long-axis in-plane method for radial artery puncture and catheterization can achieve higher first-time success rate (91.6%) and overall success rate (97.9%), while shortening the puncture time [5].

Oblique plane method

The oblique plane method can be considered as a special case of the short-axis out-of-plane combined with long-axis in-plane method. When using the oblique plane method for puncture, the operator holds the US probe with the left hand and the puncture needle with the right hand. First, the location of the radial artery should be evaluated using the short-axis out-of-plane method. Then, the US probe is rotated 30-60° based on the evaluation to make the radial artery appearing as an elliptical structure in the image. Puncture is performed when the elliptical area is the largest.

Dynamic needle tip positioning method

To some extent, dynamic needle tip localization is an improved method based on the short-axis out-of-plane method. Under the guidance of short-axis out-of-plane method, the needle tip appears as a hyperechoic bright spot between the skin and the vessel on the image. While keeping the puncture needle immobile, the US probe is moved about 2 mm towards the proximal end until the hyperechoic bright spot of needle tip disappears from image. Then, while ensuring that the probe immobile, the puncture needle is further advanced until the hyperechoic bright spot of the needle tip reappears on the image. The above procedures were repeated until the sheath needle is inserted into the radial artery lumen for over 0.5cm, and the insertion cannula is pulled out. Studies by Kiberenge et al. found that dynamic needle tip localization exhibited a higher first-time success rate than traditional palpation techniques, and shortened the puncture and placement time, regardless of the experience of physicians (**Figure 3**) [6].

Developing lines-guided localization method

The developing lines-guided localization method can also be considered a modified method of the short-axis out-of-plane method. It is now a commonly used to assist in the localization of the radial artery. This method includes two types, single developing line and double developing lines. In the single developing line-guided localization method, a developing line is fixed to the US probe, with the direction of the developing line perpendicular to the long axis of the probe. The probe is then adjusted to align the

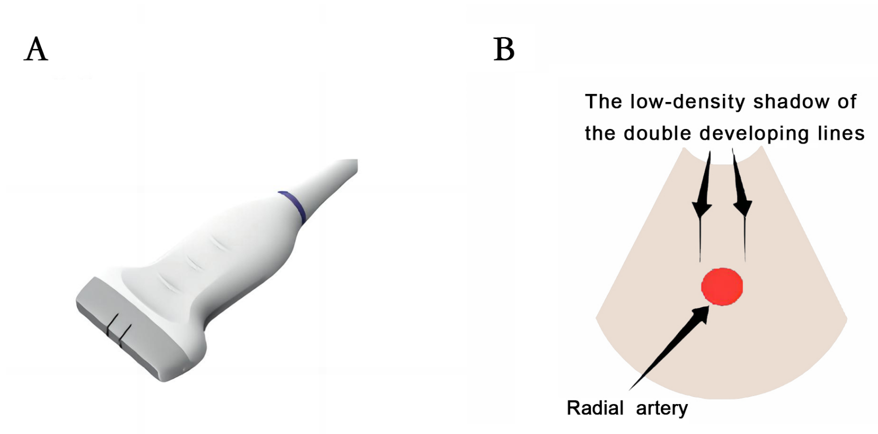

Figure 4. Schematic diagram of radial artery puncture and catheterization using the developing lines-guided localization method. (A) Double developing lines ultrasound probe; (B) Schematic ultrasound image of the radial artery using the developing lines-guided localization technique.

low-density sound shadow with the radial artery on the image, and the intersection point of the developing line and the skin is the puncture point. In the double developing lines-guided localization technique, two developing lines are fixed perpendicular to the long axis of the US probe, and then the probe is adjusted to observe the radial artery between the two low-density sound shadows on the image. The puncture needle is then placed between the two developing lines for puncture and catheterization. It should be noted that during the operation, the long axis of the US probe should always be perpendicular to the developing lines (**Figure 4**).

In addition to the commonly used US methods mentioned above, there are now various emerging methods being utilized in clinical practice, such as modified dynamic needle tip positioning method, modified long-axis in-plane method, and puncture method using a novel electromagnetic guidance US system [7-9].

Related complications

Regardless of whether traditional puncture methods or US-guided methods are used, various complications often occur during radial artery puncture and catheterization, such as hematoma, spasm, infection, embolism, and nerve injury. Understanding these complications is crucial for performing clinical radial artery puncture and ensuring safe and successful outcomes. This article summarizes the clinical manifestations, common causes, treatment, and preventive measures of common complications in US-guided radial artery puncture and catheterization, as shown in **Table 2**.

Compared with traditional puncture methods, US-guided puncture and catheterization have more advantages. Studies have shown that using US to guide radial artery puncture and catheterization can effectively reduce the incidence of complications. Therefore, when encountering patients who are not suitable for traditional radial artery puncture and catheterization, US-guided methods, such as dynamic needle tip positioning technique, should be considered, because it is more suitable for patients with coagulation dysfunction and those who are prone to hematoma [19]. In addition, Hadjivassiliou et al. proposed a guideline for US-guided catheterization of the distal radial artery via the anatomical snuffbox [20]. Their study found that using the anatomical snuffbox radial artery for puncture and catheterization could reduce the risk of radial artery occlusion, minimize the risk of hand ischemia and, prevent injury to adjacent structures. Therefore, in order to reduce the incidence of complications, the anatomical snuffbox radial artery is also an option for puncture and catheterization under US guidance.

Clinical application of US-guided radial artery puncture and catheterization

Radial artery puncture and catheterization, as an invasive operation, can directly and accurately reflect the fluctuation of the patient's blood pressure in real-time. Being more accurate and effective than non-invasive arterial pressure monitoring, it is commonly used in clinical practice for dynamic monitoring of vital signs and for blood gas analysis. Especially for patients with hemodynamic instability such as those with cardiovascular and cerebrovascular diseases, shock, complicated surgeries, and critically ill patients in intensive care units (ICU), accurate and real-time data have great clinical

Table 2. Common complications

Complications	Hematoma	Spasticity	Localized infections	Embolism [18]
Clinical manifestations	-Bruising, pain, swelling of the skin at the puncture site -Local subcutaneous petechiae, ecchymosis, purpura	-Ischemic pain and numbness in the forearm -Difficulty in pushing or rotating the catheter -Radial artery stenosis seen on radial arteriogram	-Redness, swelling and -Pain at the puncture site, -Localized dark skin color and high temperature	-Arm discomfort, pallor, cyanosis -Low hand temperature -Weak radial artery pulsations -Ischemic symptoms rarely present (if these symptoms present, it may be necrotic)
Common causes	-Injury to the radial artery due to more punctures -Low pressure and insufficient time, causing blood to penetrate subcutaneously -Penetration of the radial artery during puncture -Abnormal coagulation of the patient	-Small radial artery diameter -High level of mental stress in the patient -Having one of the following characteristics: female, light weight, hypertension, diabetes, smoking, taking beta-blockers, etc. -Too many long-time operations -Use of non-hydrophilic coated catheters or guidewires -Excessive pressure after bleeding	-Improper handling -Repeated punctures at one puncture site -Patient immunocompromised -Longer hospital stay for the patient	-Smaller radial artery diameter -Longer and stronger post-operative compressions -Female diabetic patient with history of previous transradial coronary intervention procedures, etc. -Repeated punctures -Large diameter of arterial sheath compared to radial artery diameter
Treatment	-Continuous and effective compression to stop bleeding -Cold compresses for a short period of time (<24h) to relieve pain and inflammation, and hot compresses for a longer period of time (>24h) to relieve blood stasis For patients with massive bleeding: -Use of hydrocolloid excipients to accelerate the absorption of oozing blood [13] -Heparin neutralization by intravenous fisetin -Severe cases requiring incision and drainage	-Suspend the puncture, sedate the patient and provide pain relief, apply local heat -Removing the sheath under local anesthesia -Injecting vasodilators such as nitroglycerin or verapamil -May perform a contralateral radial artery or ipsilateral femoral artery puncture if the spasm is severe and prolonged -Using for radial artery spasm [15] -Sheathless technique to relieve spasticity [16]	-Examination of wounds by methods such as wound swab culture -Proper wound management -Blood sampling for bacterial culture testing to select appropriate antibiotics	-Treatment with low molecular heparin drugs -Thrombolytic therapy with drugs such as urokinase -Transient compression of the ulnar artery -Thrombus retrieval by intervention
Preventive measures	-Carefully puncturing, stopping immediately when resistance is encountered and observed -Securing with adhesive tape and using a special hemostat after puncture if necessary [14] -Advising the patient to be less active with a light diet -Continuously and effectively compressing to stop bleeding -Enhancing post-operative observation care	-Advanced communication to keep patient informed and sedated -Pre-operative adequate anesthesia at the puncture site and local injection of 200μg of nitroglycerin to dilate the radial artery -Intraoperative intravenous injection of midazolam and fentanyl [17] -Use of a small hydrophilic coated catheter and a long ultra-smooth guidewire -Gentle intraoperative movements; if puncture fails, waiting for spasm to resolve before re-puncturing -Post-operative prophylaxis with cocktail[1] therapy	-Strict aseptic procedures before surgery -Advising the patient to pay attention to temperature changes after surgery and to consult their doctor immediately if they develop fever and chills -Immune enhancement by improving the diet after surgery	-Pre-operative Allen test -Use of smaller sized sheaths and catheters -Prompt postoperative sheath removal and reasonable control of duration of compression -Anticoagulation with higher doses of heparin -Pre-operative evaluation of radial artery patency and radial artery flow by oximetry-plethysmography test or ultrasound Doppler assessment

[1]Cocktail: commonly used medications and 200μg nitroglycerin, 2.5-5.0mg verapamil, 50U/kg or 5000U heparin. FMD, flow-mediated vasodilation.

guiding significance.

Although US-guided radial artery puncture has become increasingly popular along with the development of visualization technology, many hospitals are not equipped to use US guidance for every puncture operation due to the high cost of US equipment. Therefore, traditional blind puncture method is still the most common puncture method in clinical practice. However, due to its high dependence on operator's experience as well as the complicity of patient conditions and variations of individual in radial artery anatomy, the failure rate of traditional radial artery puncture is relatively high. For operators who cannot routinely use US, US-guided puncture can usually be used as a salvage method after traditional puncture and catheterization have failed. Liu et al. found in their research that after a failed traditional puncture, US guidance could be used as a salvage measure to reduce puncture time and the incidence of complications [21]. Dong et al. found that for patients in need of secondary radial artery puncture and catheterization, US guidance could increase the success rate and reduce the incidence of complications [22].

However, arterial puncture and catheterization operations are somewhat difficult. In clinical work, inexperienced surgeons usually consider catheterization to be more difficult than puncture. Even experienced physicians often encounter challenges such as observing obvious blood return from the puncture needle but facing difficulty in catheter insertion. Since the diameter of the puncture needle is smaller than the diameter of the sheath, which is thinner than the radial artery, the puncture needle may not locate at the center of the artery despite successful puncture and blood return observed. Therefore, although there is blood backflow, difficulties may arise in catheterization. US guidance has the advantage of being intuitive, displaying the images in real-time, which can help the operator clearly observe the structures around the radial artery and instantaneously track the needle tip during the puncture process. These can effectively improve the success rate of puncture. Therefore, it is suitable for widespread use in medical education.

Several studies on US-guided radial artery puncture and catheterization in intern training have shown that the US-guided method helps interns to quickly and accurately acquire the puncture techniques. Chen et al. found that dynamic needle tip positioning method can improve the success rate of puncture and catheterization in interns compared with the traditional blind probing method [23]. Dong et al. randomly divided 116 residents into a new US-guided teaching group (double developing lines-guided localization method) and a traditional US-guided teaching group (short-axis out-of-plane method), and found that radial artery puncture and catheterization under the sound shadow-assisted US guidance significantly improved the first-time success rate (78.43% vs. 58.00%, odds ratio=0.380; 95% CI=0.159 - 0.908; $P=0.027$), shortened the catheterization time (14.36±3.31 vs. 18.02±4.95, $p<0.001$), and facilitated standardized teaching for residents [24].

For beginners, it is recommended to start with the simpler one, short-axis out-of-plane method, followed by the long-axis in-plane method and short-axis out-of-plane combined with long-axis in-plane method. By combining basic exercises with training, beginners can solidify their proficiency in this skill. With the development of visual technology, US-guided radial artery puncture teaching can not only improve the efficiency of learning for beginners, but also effectively increase the success rate of the operation compared to traditional teaching methods. Additionally, simulation training with some auxiliary devices can be used during training. Studies have shown that using vascular models for simulation training can effectively improve the first-time success rate of US-guided radial artery catheterization in actual patients, and help beginners to better acquire the dynamic needle tip positioning method [25].

Application of US-guided radial artery puncture in special patient groups

Studies have shown that for some special patient groups, such as those with septic shock, US-guided radial artery puncture can improve the success rate of puncture, shorten the duration of the procedure, and reduce the incidence of complications compared to traditional puncture methods [26]. In addition, US guidance should be considered with priority for infants, obese patients, elderly patients, patients with weak pulses, severe hypotension, or abnormal coagulation function, and critically ill patients that require special attention during radial artery puncture.

Infants

The radial artery of infants is narrow and straight with weak pulsations and is easily displaced during puncture. Additionally, the small size of the radial artery poses a challenge in visualizing the hyperechoic spot of the needle tip on US images, especially when it is near the radial artery, making it difficult to control the position of the needle tip in real-time during puncture [27]. Furthermore, infants in the perioperative period often have organ deformities and other issues, which significantly increases the difficulty of puncture. However, ordinary US-guided puncture techniques can hardly address these difficulties effectively, so modified US-guided puncture techniques are commonly used in clinical practice.

Quan et al. randomly divided infant patients into two groups, a new US group (double developing lines-guided localization method) and a traditional US group (short-axis out-of-plane method), and found that the first attempt success rate of intubation in the new US group (90%) was significantly higher than that in the traditional US group (60%) [28]. Wang et al. randomized 72 infants aged 1-12 months into a long-axis in-plane combined with short-axis out-of-plane (LAX-IP-SAX-OOP) group and a modified dynamic needle tip positioning (MDNTP) group, and found that the first attempt success rate of intubation in the LAX-IP-SAX-OOP group was significantly higher than that in the MDNTP group (75.0% vs. 36.1%), and the intubation time was significantly shorter in the LAX-IP-SAX-OOP group [29]. Yang et al. found that by adding a scale to the US screen and probe, the correlation to the radial artery positions displayed by both could provide accurate arterial localization and guidance for the operator, thereby helping them locate the needle tip faster and improving the success rate of infant puncture [30]. In addition, there is a new method of single-operator laser-assisted US-guided puncture, which can improve the first attempt success rate of radial artery insertion in children under 2 years old and make the US probe more stable [31].

Here are some tips for radial artery puncture in infants, including: i) for pediatric radial artery puncture, the success rate is the highest when the depth of the radial artery is about 2-4mm [32]; ii) puncture can cause some degree of pain, which is a significant issue to be addressed for infant puncture. It is necessary to use child-friendly language to keep their emotions stable before puncture, and appropriate needles can also alleviate the pain of infants; iii) studies have shown that a puncture angle of 30-45° can increase the first-attempt success rate of radial artery puncture and reduce the incidence of related complications; the needle insertion angle increases with the body weight of the infant and the diameter of the radial artery [33]; iv) puncture can be combined with the subcutaneous injection of 2ml of 0.9% NaCl to deepen the depth of the radial artery and thereby increase the success rate of puncture [34].

Considering the characteristics of infant radial artery and the advantages and disadvantages of conventional US methods (short-axis and long-axis), we found that the short-axis method is more suitable for infants. This is because the infants have thinner blood vessels and the proximity of the target blood vessels to the surrounding anatomical structures. The thinner blood vessels of infants make it difficult to obtain images using the long-axis method.

Elderly patients

Elderly patients often have underlying diseases and hemodynamic instability, so continuous arterial blood pressure monitoring is often required in clinical practice. However, due to weak radial artery pulsation, arterial wall sclerosis, poor elasticity, and loose subcutaneous tissue, the puncture is easy to fail, which may directly lead to the occurrence of complications such as hematoma. Therefore, US-guided puncture is often used in clinic. In addition, due to the frequent occurrence of cognitive dysfunction in elderly patients after surgery, the clinical compliance is also compromised. Therefore, faster and more convenient puncture methods, such as oblique plane puncture and developing lines-guided localization technique, are more suitable.

Chen et al. compared the oblique plane puncture method, short-axis out-of-plane and long-axis in-plane in elderly patients and found that the oblique plane puncture method not only shortened the puncture time but also increased the success rate of puncture [35]. Ye et al. found that double developing lines-guided localization technique shortened the time of positioning and puncture, and improved the success rate of initial puncture in elderly patients [36]. Shim et al. randomized elderly patients into a dynamic needle tip positioning group (group D) and a short-axis out-of-plane group (group C), and their results showed that the first attempt success rate in group D (89%) was significantly higher than that in group C (72%), and the incidence of hematoma in group D (16%) was significantly lower than that in group C (47%) [37]. For elderly patients over 70 years old, the use of dynamic needle tip positioning method can improve the success rate of initial radial artery catheterization and reduce the incidence of complications.

In addition, it should also be noted that due to the loose subcutaneous tissue in elderly patients, the position of the catheter may be affected during needle withdrawal. Operators should withdraw the needle gently and slowly, and also maintain constant vigilance on the position of the catheter [38].

Obese patients

With the increasing living standard, the number of obese patients is gradually increasing. For obese patients, the large accumulation of subcutaneous fat makes it difficult to palpate arterial pulsations, thus bringing great challenges in traditional blind probing procedures. In addition, repeated punctures can cause discomfort to patients and may lead to various complications.

Zou et al. randomly divided 240 obese patients into a control group, a single developing line-guided localization technique group, and a double developing lines-guided localization technique group, and compared the first attempt success rate, operation time and incidence of complications among the three groups [39]. They found that both single and double developing lines-guided localization techniques improved the first attempt success rate of radial artery catheterization under US guidance in obese patients (control group vs. single developing line vs. double developing lines = 71% vs. 90% vs. 91%), while reducing the incidence of complications (control group vs. single developing line vs. double developing lines = 29% vs. 10% vs. 9%).

One of the difficulties in performing radial artery puncture on obese patients is to maintain the extension of the wrist joint. A study reported improved the success rate of radial artery puncture and catheterization in obese patients and alleviated pain with the clinical use of inflatable radial artery puncture fixation device [40].

Factors affecting the success rate of radial artery puncture

"Hit the nail on the head" during radial artery puncture is a widely accepted approach among anesthesiologists, because it can reduce the incidence of radial artery spasm, alleviate patient pain and shorten operation time. Therefore, to achieve a successful radial artery puncture with "one-shot", it is necessary to understand the factors that affect the puncture success rate, and then to achieve better radial artery catheterization placement with US guidance.

Radial artery anatomy

The diameter, vertical depth, associated variation of artery and whether the vessel is filled are main factors that directly affect the success rate of puncture.

Filled vessels are easier to palpate and visualize. Lee et al. found that the average diameter of the radial artery was 2.2 ± 0.4 mm, and the larger the diameter of the radial artery, the higher the success rate of puncture, and vice versa [41]. Besides, appropriate radial artery depth is also a guarantee of successful puncture. When the radial artery is located deep within the tissue, puncturing it at a small angle would require a longer needle path. To shorten the needle path and improve the chances of success, a larger angle of entry may be attempted. However, a larger angle reduces the contact area between the puncture needle and the blood vessel, making the procedure more challenging. Nakayama et al. found that when the depth of the radial artery was 2-4 mm during radial artery puncture and catheterization in children, the puncture time was reduced and the success rate was improved, and for radial arteries with a depth of less than 2 mm, saline can be subcutaneously injected to increase the depth to 2-4 mm [32]. Nie et al. reported a 20.3% anatomical variation rate of radial artery in Chinese people [42]. This is the primary reason for the failure of puncture.

Operator experience

From the perspective of the operator, their long-term experience and solid skills play a crucial role in the success of the operation.Relevant studies have shown that anesthesiologists with more experience in radial artery puncture and catheterization have a higher success rate than those with less experience [43]. In particular, experienced doctors often use the advantages of US-guided radial artery puncture to improve the success rate [7]. Wang et al. compared the total success rate of US-guided radial artery puncture and catheterization among three anesthesiologists with different clinical training durations, and found that anesthesiologists with longer training time showed an obvious better performance during US-guided radial artery puncture and catheterization [5].

Both the operator's technical level and famil-

Table 3. Radial artery diameter

Classification	Crowd	Mean diameter of the radial artery
Ethnicity	Chinese	2.38±0.56mm
	Japanese	2.4±0.4mm
	Korean	2.60±0.4mm
Age	Adults	2.2±0.4 mm
	Pediatric	1.2±0.3mm [48]
Sex [49]	Men	2.69±0.40mm
	Women	2.43±0.38mm

iarity with the US equipment affect the success rate of puncture and the incidence of complications. Before operation, operators need to perform the Allen test on the patient, and during the operation, the puncture should be performed accurately and in a sterile environment. In addition, patients, especially for pediatric patients, may experience pain and discomfort during radial artery puncture, which can easily lead to puncture failure. Therefore, how to better manage pain in patients is a factor affecting the success of radial artery puncture. Before the operation, operators should fully communicate with the patients. During the puncture, lidocaine can be applied to the puncture site to reduce vascular constriction caused by pain. Zeng et al. found that using a compound lidocaine cream on ICU patients could alleviate the pain of radial artery puncture [44]. In addition, multiple training sessions are helpful in improving the operator's ability. Research has shown that the more a physician knows about the puncture site and technique, the less time and number of attempts they need for puncture [45].

Patient factors

Considering factors related to the patient, sex, age, race, and physical condition are all relevant factors affecting the success rate of puncture.

A study has shown that the radial artery diameter is larger in males than in females, and the thinner vessels in females make puncture more difficult [46]. However, for female patients, the radial artery diameter can be enlarged by subcutaneously injecting 50 ug nitroglycerin in combination with 10 mg lidocaine [47]. As shown in **Table 3**, there are various factors that can lead to differences in radial artery diameter reported by existing studies.

From the data in the table, it can be seen that age also has a certain impact on radial artery puncture. Pediatric patients are more prone to puncture failure and a variety of complications due to their smaller radial artery diameter. Puncture in elderly patients are another challenge due to their fragile and less elastic blood vessels. In addition, patients with pathological obesity tend to have thick subcutaneous fat and tissue dispersal, which can also affect the radial artery puncture and catheterization outcome.

Puncture techniques

As an invasive operation technique, radial artery puncture involves many operative techniques in practical applications, which can help increase the success rate of radial artery puncture. The operative techniques lie in the angle of needle insertion, the angle of the wrist, the position of puncture, and the selection of puncture needle and probing device.

Studies have shown that comparing with the approach of the US probe perpendicular to the radial artery, the approach of the US probe perpendicular to the puncture needle can significantly reduce the first radial artery catheterization time and total puncture time [50]. Zhang et al. found that compared with a 90° needle insertion angle, a 30-45° needle insertion angle increases the contact area between the puncture needle and blood vessel, improves the success rate of the first puncture, and reduced the incidence of hematoma [33]. Existing publications indicate that when performing radial artery puncture in adult patients, inserting the catheter at a wrist angle of 45° can significantly shorten the catheterization time and increase the first success rate [51, 52]. The superficial and most pronounced pulsation is 2-3 cm proximal to the transverse wrist, which is usually the site chosen for the puncture. Study has reported that the distal quarter of the forearm can be considered as the "best insertion site" for radial artery catheterization under US guidance [53]. High-frequency probes, with greater image resolution, can clearly distinguish adjacent nerve and small arterial branches and are suitable for patients with shallow vascular lumina, such as infants and young children. Low-frequency probes, however, are mainly suitable for patients with deeper target vessels, such as obese patients. Saima et al. measured a "safe" segment (the length between the styloid process and the distal edge of the "parallel" segment) using an US device. It was found to be approximately 6.8-11.6 cm in males, with an average of about 9.4 cm, and 5.4-11.0 cm in females, with an average of about 8.2 cm [54].

Conclusion

Due to its advantage of visualization, US is currently a hot topic in clinical practice. The use of US-guided radial artery puncture and catheterization has resolved many disadvantages of traditional blind probing methods, reduced the operator's stress, and improved the success rate of puncture and catheterization. However, due to the high cost of US equipment and the high level of technical difficulty, this method poses new requirements for operators to use US technology.

It can also be observed that many of the newly developed US methods are modifications of basic methods, which laid a foundation for innovations and improvements of better puncture methods. However, US is still in a two-dimensional space, so there are unavoidable limitations. It is conceivable that three-dimensional visualization technology, if applied to the preoperative evaluation or guidance of radial artery puncture and catheterization, may further improve the success rate of puncture.

In addition, most of the reports on physician training of US-guided arterial puncture only focus on the application effects of a certain US method. There is limited comprehensive analysis available to determine which US method is more suitable for beginners to master. Based on theoretical analysis, we proposed that comparing with traditional methods, US-guided radial artery catheterization may help beginners master radial artery puncture more effectively, but the specific utility still needs to be verified by further research.

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