Radial Artery Cannulation: A Comprehensive Review of Recent Anatomic and Physiologic Investigations

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Consistent anatomic accessibility, ease of cannulation, and a low rate of complications have made the radial artery the preferred site for arterial cannulation. Radial artery catheterization is a relatively safe procedure with an incidence of permanent ischemic complications of 0.09%. Although its anatomy in the forearm and the hand is variable, adequate collateral flow in the event of radial artery thrombosis is present in most patients. Harvesting of the radial artery as a conduit for coronary artery bypass grafting, advances in plastic and reconstructive surgery of the hand, and its use as an entry site for cardiac catheterization has provided new insight into the collateral blood flow to the hand and the impact of radial arterial instrumentation. The Modified Allen's Test has been the most frequently used method to clinically assess adequacy of ulnar artery collateral flow despite the lack of evidence that it can predict ischemic complications in the setting of radial artery occlusion. Doppler ultrasound can be used to evaluate collateral hand perfusion in an effort to stratify risk of potential ischemic injury from cannulation. Limited research has demonstrated a beneficial effect of heparinized flush solutions on arterial catheter patency but only in patients with prolonged monitoring (>24 h). Conservative management may be equally as effective as surgical intervention in treating ischemic complications resulting from radial artery cannulation. Limited clinical experience with the ultrasound-guided arterial cannulation method suggests that this technique is associated with increased success of cannulation with fewer attempts. Whether use of the latter technique is associated with a decrease in complications has not yet been verified in prospective studies. Research is needed to assess the safety of using the ulnar artery as an alternative to radial artery cannulation because the proximity and attachments of the ulnar artery to the ulnar nerve may potentially expose it to a higher risk of injury.

(Anesth Analg 2009;109:1763–81)

Continuous arterial blood pressure monitoring via direct radial artery cannulation along with easy access for blood sampling can provide the clinician with vital information in the perioperative period.[1] Historically, this technique can be traced to 1733 when Stephen Hales inserted a narrow brass pipe into an artery of a horse and fitted a 9-foot-long vertical glass tube to the pipe. He witnessed how the systemic pressure pushed the blood to a height of 8 feet 3 inches. Catheterization of arteries by surgical exposure was described by Farinas and Radner in the first half of the 20th century.[2] In humans, continuous recording of pulse waves and arterial blood pressure with small plastic catheters was first described in 1949 by Peterson et al.[3] The catheters were inserted percutaneously into the brachial artery through a metal needle and used during the perioperative period for as long as 10 h. Percutaneous catheterization with a polyethylene catheter through a large-bore needle in the femoral artery was first described by Peirce[4,5] in 1951. Soon thereafter, Seldinger[6] introduced the percutaneous catheterization method over a guidewire. Percutaneous cannulation of the radial artery with a teflon catheter was described by Barr[7] in 1961. However, most radial artery catheters between 1955 and 1970 were inserted by surgical cutdown.

The consistent anatomic accessibility, ease of cannulation, and a low rate of complications make the radial artery the preferred site for arterial cannulation.[8] Although some consider the ulnar artery the larger of the 2 arteries supplying the hand,[9–11] its cannulation can be technically challenging because of its more tortuous and deeper course.[12] In 1990, the

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Accepted for publication July 21, 2009.

Supported in part by Departmental Funds.

Martin J. London is Section Editor of Perioperative Echocardiography and Cardiovascular Education for the Journal. The manuscript was handled by Charles W. Hogue, Jr., Associate Editor-in-Chief for Cardiovascular Anesthesiology and Dr. London was not involved in any way with the editorial process or decision.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.anesthesia-analgesia.org).

Reprints will not be available from the authors.

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DOI: 10.1213/ANE.0b013e3181bbd416

number of arterial catheters placed perioperatively was estimated to be 8 million in the United States and 2.5 million in Europe.[13] An increasingly older and medically complex patient population, together with an increase in the complexity of surgical procedures, have likely led to an increase in the perioperative use of this procedure. Invasive arterial monitoring, nonetheless, is associated with risk including bleeding, hematoma, pseudoaneurysm, infection, nerve damage, and distal limb ischemia.[14–18] The use of the radial artery as an alternative arterial conduit for coronary artery bypass grafting,[19,20] its use for newer reconstructive hand surgeries,[21,22] and as an alternative route for diagnostic and therapeutic cardiac catheterization[23–26] has provided new knowledge about the anatomy and physiology of this artery and perfusion of the hand.

We present a detailed review of issues important for radial artery cannulation including the anatomy of the blood supply to the hand, complications and methods for predicting and treating such complications, and a discussion of the efficacy of heparinized versus nonheparinized solutions to maintain arterial catheter patency.

ANATOMIC CONSIDERATIONS

The radial and ulnar arteries form the arterial blood supply to the forearm and the hand. The radial artery originates from the brachial artery in the cubital fossa, medial to the biceps tendon, and continues its course toward the styloid process of the radius.[27] Variants in the origin or in the course of the radial artery[28–39] have been found in up to 30% of individuals[28] (Table 1). Less anatomic variation is found in the distal forearm, where arterial cannulation is usually performed.[28] The ulnar artery originates medial to the biceps tendon in the cubital fossa and gives rise to the common interosseous artery, continuing its course toward the lateral side of the pisiform bone.[27] Anatomic variation in the origin and course of the ulnar artery is relatively infrequent (3%–5%).[28]

The "classic" anatomic literature views the radial artery as the smaller of the 2 major hand arteries,[11,27,43] implying that radial artery removal is safe and better tolerated than removal of the ulnar artery. There is strong evidence that the ulnar artery diameter is larger in the cubital fossa where both arteries arise.[44,45] However, this relationship is less clear at the wrist[44,46—49] because the ulnar artery gives off multiple branches in the forearm, whereas the radial artery serves mainly as an arterial conduit to the hand (Table 2).[44,45,49–51] This view is further supported by a recent postmortem study measuring the internal diameters of the radial and ulnar arteries at the wrist.[50] The radial artery was larger or equal to the ulnar artery in 87% of arms, and the mean radial artery diameter was reported to be 26%–28% larger than that of the ulnar artery. The radial artery diameter was also found to be significantly larger than the ulnar artery diameter (2.45 vs 2.3 mm, $P = 0.0001$) in a retrospective review of duplex ultrasound findings from 327 patients.[54]

Table 1. Variants in the Origin or in the Course of the Radial Artery

Variants in the origin of the radial artery
High origin, defined as radial artery arising either from the brachial or axillary artery proximal to the antecubital fossa, has been found in 2.4% to 14.3% of upper extremities.[28–30,38–40]
Opposite origin of the radial and ulnar arteries to the usual arrangement, defined as the origin of the radial artery from the medial and of the ulnar artery from the lateral side of the brachial artery, has been rarely reported.[31,32]
Absent radial artery with an estimated incidence of 0.03% is rare.[36,37,40,41] The anterior interosseous artery was found to provide the blood supply.
Duplication of the radial artery. Two radial arteries in the forearm have been infrequently described (0.2%),[28,33,38,40] with only 1 case report of a real duplication of the radial artery with relation of brachial artery.[40,41]
Variants in the course of the radial artery
Crossing of the radial artery over the brachial artery.[34]
Radial artery running to the forearm in front of the aponeurosis of the biceps brachii muscle.[34]
Radial artery passing deep to the tendon of the biceps brachii muscle.[35]
Tortuosity of radial and brachial artery that can be associated with a more challenging anatomy for instrumentation (4.2%–5.2%).[38,42]
Superficial radial artery, i.e., radial artery with normal origin that crosses over the tendons that define the snuffbox (0.5%).[40]

At the level of the wrist and hand, the radial and ulnar arteries create a dense anastomotic network of 4 arches, which provide the arterial blood flow to the hand (Fig. 1). Three of these arches occur on the palmar side of the hand and include the palmar carpal arch, the deep palmar arch, and the superficial palmar arch. The arterial network on the dorsal side consists of the dorsal palmar rete. The superficial palmar arch is formed by the terminal part of the ulnar artery.[27,43] The deep palmar arch is formed by the terminal part of the radial artery.[27,43] The deep palmar arch gives rise to 3 or 4 palmar metacarpal arteries,[22,43] and the superficial palmar arch to 3 or 4 common palmar digital arteries.[56] The superficial palmar arch and deep palmar arch are the most clinically significant arches because they provide blood flow to all the digits of the hand.

Although the blood supply of the hand has been studied by numerous investigators,[22,28,46,47,52,55,57–65] substantial variability in the anatomy of the superficial and deep palmar arches seems to be the only consistent finding (Fig. 1, Table 3).[60] Jaschtschinski[59] in 1897 originally subdivided the superficial palmar arch into 2 types: complete and incomplete. This classification is still useful today to identify patients with an anastomotic network potentially inadequate to tolerate radial artery ligation, particularly the thumb (Fig. 1, Table 3).[60,68] Theoretically, a patient with a complete superficial palmar arch and deep palmar arch should be able to tolerate ligation of the radial or ulnar artery because collateral flow will preserve perfusion to the

Table 2. Inner Diameter of the Radial and Ulnar Arteries Measured at the Level of the Wrist

Study	Radial artery	Ulnar artery
Fazan et al.,[49] 46 hands, 25 cadavers	Complete superficial palmar arch: R, 3.1 mm ± 0.2 and L, 3.1 mm ± 0.2 Incomplete superficial palmar arch: R, 2.6 mm ± 0.3 and L, 2.7 mm ± 0.2	Complete superficial palmar arch: R, 2.5 mm ± 0.2 and L, 2.6 mm ± 0.1 Incomplete superficial palmar arch: R, 2.6 mm ± 0.2 and L, 2.6 mm ± 0.2
Bilge et al.,[48] 50 hands, 26 cadavers	Complete superficial palmar arch: R, 3.50 mm ± 0.64 and L, 3.42 mm ± 0.65 Incomplete superficial palmar arch: R, 3.85 mm ± 0.85 and L, 3.55 mm ± 0.61	Complete superficial palmar arch: R, 3.57 mm ± 0.75 and L, 3.59 mm ± 0.74 Incomplete superficial palmar arch: R, 3.42 mm ± 0.30 and L, 3.55 mm ± 0.46
Gellman et al.,[52] 45 hands	2.6 mm (2.3–5 mm)	2.5 mm (1.4–4.5 mm)
Haerle et al.,[44] 41 cadavers	3.3 mm (3.1–3.5 mm)*	2.6 mm (2.5–2.8 mm)
Riekkinen et al.,[50] postmortem angiogram in 41 cadavers	R, 3.2 mm* and L, 3.0 mm*	R, 2.5 mm and L, 2.4 mm
Kohonen et al.,[53] biplane ultrasonography, 145 patients scheduled for elective heart surgery	Proximal diameter: 3.06 ± 0.63 mm (range, 1.2–5.3 mm) Distal diameter: 2.6 ± 0.46 mm (range, 0.9–3.06 mm)	Proximal diameter: 3.25 ± 0.72 mm (range, 1.3–5.8 mm) Distal diameter: 2.39 ± 0.49 (range, 1.0–3.5 mm)

R = right; L = left.

* The mean diameter of the radial artery significantly ($P < 0.001$) larger than the mean diameter of the ulnar artery.

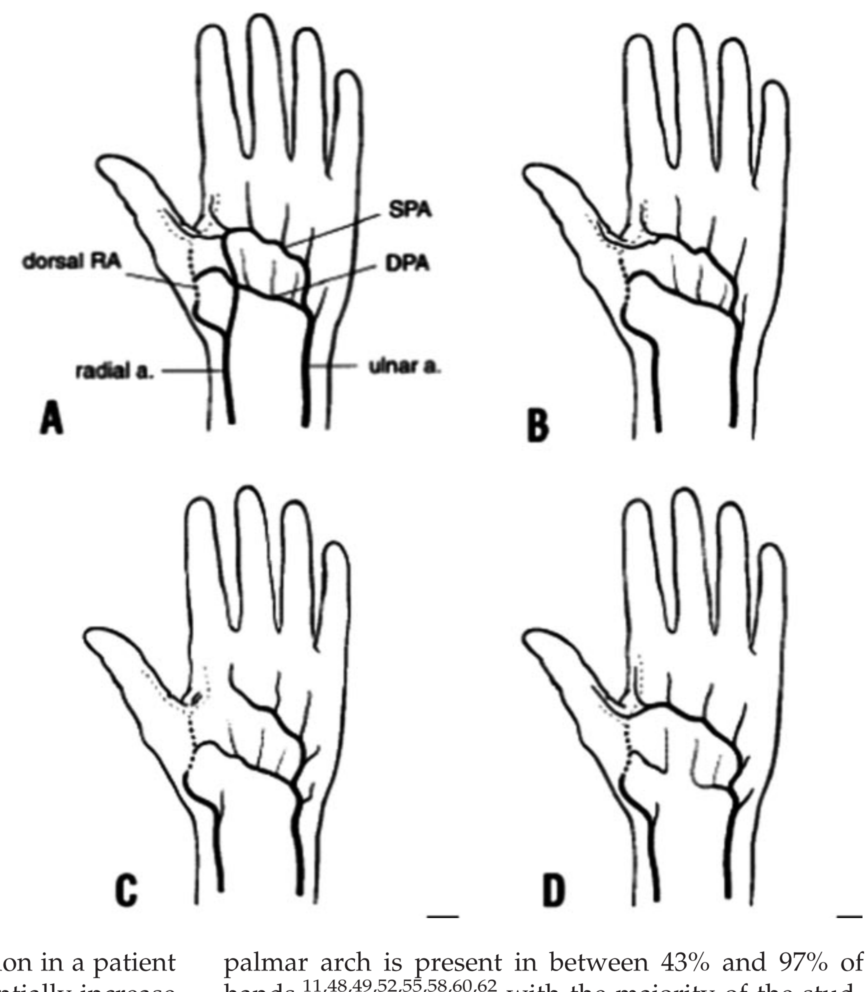

Figure 1. Variations in the anatomy of the superficial palmar arch (SPA) and the deep palmar arch (DPA). A, Classic (and complete) SPA: the SPA from the ulnar artery (UA) supplies the index finger and thumb and anastomoses with the superficial palmar branch of the radial artery (RA). B, Complete SPA: the SPA from the UA supplies the thumb. Complete DPA: the distal end of the DPA anastomoses with the deep palmar branch of the UA. C, Incomplete SPA: the SPA does not provide a metacarpal branch to supply the thumb. D, Incomplete DPA: no continuity is found between the DPA of the UA and the RA. The dotted line represents the dorsal artery. (Reproduced from Ruengsakulrach et al.[55] with permission.)

digits. Conversely, radial artery occlusion in a patient with 2 incomplete arches might substantially increase the risk for digital ischemia.[60]

Even though the described anatomic variations of the superficial palmar arch and deep palmar arch are numerous,[22,28,46,47,52,55,57–65] few general statements can be made. First, a complete superficial palmar arch is present in between 43% and 97% of hands,[11,48,49,52,55,58,60,62] with the majority of the studies showing its presence in ≥80% of patients. Second, the incidence of a complete deep palmar arch varies between 67% and 100%, with most studies reporting a complete deep palmar arch in at least 90%–95% of hands. It is important to note that multiple techniques

Table 3. Anatomical Variations in the Arterial Patterns of the Deep[a] and Superficial[b] Palmar Arches

Authors	Specimens	Incomplete SPA	Complete SPA	Incomplete DPA	Complete DPA
Edwards[22]	Not specified			5%	95%
Coleman and Anson[11]	650 hands	21.5%	78.5%	3%	97%
Ikeda et al.[62]	220 hands, 120 cadavers	3.6%	96.4%	23.1%	76.9%
Jelicic et al.[58]	50 hands	3%	97%		
Mezzogiorno et al.[66]	60 hands			33.3%	66.7%
Olave and Prates[67]	60 hands, 30 cadavers,			1.7%	98.3%
Gellman et al.[52]	45 hands	15.5%	84.4%	0%	100%
Ruengsakulrach et al.[55c]	50 hands	34%	66%	10%	90%
Fazan et al.[49]	46 hands, 25 cadavers	57% Right, 48% left	43% Right, 52% left		
Loukas et al.[60]	200 hands, 100 cadavers	10%	90%	0%	100%
Bilge et al.[48]	50 hands, 26 cadavers	14%	86%		

[a] DPA, deep palmar arch, is defined as complete or incomplete based on the presence of a connection between the branches of the radial and ulnar arteries.[48,55,60]

[b] SPA, superficial palmar arch, is commonly defined as complete when it supplies digits II–V and the ulnar side of the thumb, or when the terminal branch of the ulnar artery extends into the first interosseous space of the hand.[48,55,60] The superficial palmar arch is considered incomplete when the terminal ulnar artery supplies only the digits III–V.[48,55,60]

[c] All patients had at least 1 complete arch.

Table 4. Prevalence of Preexisting Disease in the Radial Artery Using Doppler Ultrasound Technique

Study	Results	Predictors of pathological radial artery changes
Hosono et al.[76] 55 patients prior to CABG	Atherosclerotic changes: 7.3%	NA
Ruengsakulrach et al.[74] 73 patients prior to CABG	Overall incidence of radial artery abnormality: 31.5%; intimal or medial calcification: 24.7%; echogenic plaques: 6.8%	Any ultrasound-detected radial artery disease: carotid disease and peripheral vascular disease
Rodriguez et al.[77] 346 arms, 187 patients prior to CABG	Calcifications: 8.7%	NA
Nicolosi et al.[78] 102 men (49 with diabetes) referred to a vascular laboratory	Dense calcifications: 34% diabetics versus 9.6% nondiabetics, $P = 0.007$; complete absence of calcifications: 18% diabetics versus 52% nondiabetics, $P = 0.000$	Calcifications in the radial artery: diabetes
Oshima et al.[75] Intravascular ultrasound 58 patients prior to transradial cardiac procedures	Calcification: 8.6%; judged as unsuitable for bypass conduit: 6.9%	No significant correlations

CABG = coronary artery bypass graft; NA = not applicable.

have been used in these anatomic studies (e.g., gross dissection,[11] latex injection,[52] or stereoscopic arteriographs[62]) each of which may result in different measurements. Finally, physiologic studies using noninvasive methods reported a complete superficial palmar arch in between 84% and 95% of hands. Although physiologic studies cannot necessarily identify anatomic structures, these results suggest a high physiologic adaptability of the hand's dense arterial network[47,56,63–65,69] (Web Supplement Table 1, see Supplemental Digital Content 1, http://links.lww.com/AA/A30).

PREVALENCE OF RADIAL ARTERY ATHEROSCLEROSIS

The popularity of the radial artery as a conduit for coronary revascularization has led to an increased interest in assessment of the prevalence of atherosclerotic disease of this artery. Advancing age is associated with adaptive thickening of the intima.[70,71] This process differentially affects various arterial beds and can vary between relatively harmless adaptive intimal thickening[70] to advanced atherosclerotic lesions.[71] Regardless of intimal involvement, the media can develop calcifications (Mönckeberg's calcifications).[72] The incidence of atherosclerosis demonstrated by ultrasound imaging has been reported to be far less common in the radial artery than in the common carotid artery.[73] Preoperative Doppler ultrasound examination in patients with cardiac disease demonstrates atherosclerosis and calcification of the radial artery in 7%–9% and 8%–25% of patients, respectively[74–77] (Table 4). The incidence of calcifications in diabetic patients (Fig. 2) has been reported to be as high as 82%, with dense calcifications in 34%.[78]

Investigators using histopathologic and morphometric analyses reported that in patients with coronary artery disease, the radial artery is more likely to

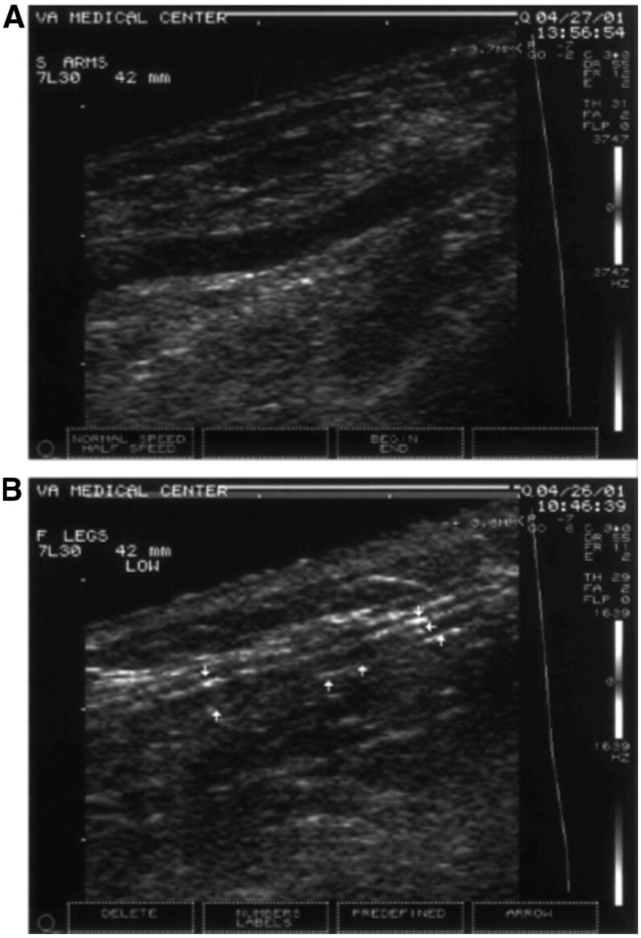

Figure 2. Ultrasound images showing longitudinal views of normal (A) and calcific (B) radial arteries. The normal vessel has a thin, homogeneous wall and smooth luminal surface (A). The calcified artery (B) is characterized by multiple echogenic areas in the vessel wall (vertical arrows) and by an irregular luminal surface. The horizontal arrow indicates a calcific plaque extending into the vessel lumen. (Reproduced from Nicolosi et al.[78] with permission.)

have intimal hyperplasia, atherosclerosis, and medial calcification than the internal mammary artery (Table 5).[79–82] Intimal hyperplasia has been reported in 67%–94%,[79–81,83] atherosclerosis in 5%–6%,[80,83] and medial calcification in 6%–13% of radial artery samples.[80,83] Atherosclerosis of the radial artery is a segmental disease with predilection to the distal part of the artery.[83] The most consistently reported predictors of radial artery atherosclerosis and medial calcifications are peripheral vascular disease, smoking, age, and diabetes (Table 5).[74,78,80,81,83] In contrast, radial artery specimens obtained in 59 hemodialysis patients at the time of fistula surgery showed no atherosclerotic changes and an incidence of intimal hyperplasia of 76%.[84] Old age and diabetes were identified as risk factors for the latter. The incidence of ischemic heart disease was significantly greater in the group with intimal hyperplasia (48% vs 14%, $P = 0.035$).[84]

Indwelling radial artery catheters have been found to induce local injury (e.g., intimal damage and proliferation).[85] Even cannulation for only 6 h has been associated with arterial wall scarring. Significant long-term structural changes have been reported after transradial cardiac catheterization[86–90] leading to a significant reduction in the radial artery diameter,[86,89] stenosis (segmental or diffuse), or even radial artery occlusion.[87,91] The incidence of radial artery occlusions 1 mo after transradial artery coronary angioplasty was reported to be 2.8%.[92]

EVALUATION OF HAND CIRCULATION BEFORE RADIAL ARTERY CANNULATION

Allen's Test

Both the necessity and the optimal method to assess adequacy of collateral blood flow to the hand before radial artery cannulation are controversial.[16] Clinically, the Allen's Test is most often used to evaluate baseline hand circulation. It was first described in 1929 by Dr. Allen[93,94] as a means to evaluate collateral circulation simultaneously in both hands of patients with thromboangiitis obliterans, and then modified by Wright[95,96] in the 1950s as a means to evaluate flow in a single hand. The Modified Allen's Test has been subsequently used to assess collateral blood flow to the hand. With firm occlusive pressure held on both the radial and ulnar arteries, the patient is asked to clench his or her fist several times until the palmar skin is blanched. The arteries should be compressed proximal to the expected tip of the arterial catheter because proximal branches of radial artery to the hand circulation could elicit falsely normal results.[97,98] The patient is then instructed to unclench the fist, and then ulnar artery pressure is released while maintaining occlusion of the radial artery. Overextension of the hand and wide spreading of the fingers should be avoided because it can lead to falsely abnormal results.[99,100] The time required for palmar capillary refill is noted. The test is then repeated with the radial artery pressure released while maintaining occlusion of the ulnar artery (inverse Modified Allen's Test). Although it is simple to perform, there are several limitations including the primary end point (return to normal skin color), which is prone to observer variability.[99] Not unexpectedly, a wide range of values for the time required for hand reperfusion has been reported (from 3 to 15 s).[14,68,85,97,99–107] The frequency of an abnormal Modified Allen's Test (variously defined) ranges from $<$1% to 27%.[100,108] Its clinical reliability as a screening tool varies greatly as well. Ruengsakulrach et al.[68] compared the Modified Allen's Test ($\leq$10 s) with Doppler ultrasonography of the thumb artery in 71 patients and found the Modified Allen's Test to have a sensitivity of 100% and specificity of 97%. They further reported use of the Modified Allen's Test as a screening tool in 1657 radial artery harvests from 1323 patients with no ischemic complications.[68] Others reported a similar lack of ischemic complications when the Modified Allen's Test was used to guide suitability of radial artery

Table 5. Prevalence of Preexisting Disease in the Radial Artery (RA) Using Histopathologic and Morphometric Analyses

Study	Results	Predictors of pathological RA changes
Kaufer et al.[81]		
106 RA specimens, 102 patients	Grade 0 atherosclerosis, IMR ≤0.25: 46.2% Grade 1 atherosclerosis, IMR 0.25–0.5: 25.5% Grade 2 atherosclerosis, IMR 0.5–0.75: 19.8% Grade 3 atherosclerosis, IMR >0.75: 6.6% Grade 4 atherosclerosis, lumen completely obliterated by thickening or thrombosis, or both: 1.9%	Atherosclerosis: male gender, age, presence of diabetes, aortoiliac, and femoral-popliteal atherosclerosis
Ruengsakulrach et al.[80]		
Distal RA specimens, 150 patients	Intimal hyperplasia: 94% Medial calcification: 13% Atherosclerosis: 5%	Intimal hyperplasia and atherosclerosis: Peripheral vascular disease, smoking, age, and diabetes
Kane-ToddHall et al.[79]		
RA specimens in 177 patients	Degree of estimated stenosis: atherosclerosis grade •Minimal (<5%): 42%, mild (5%–30%): 56%, moderate (30%–40%): 2%, severe (>40%): 1% •Medial sclerosis: 46% •Medial calcification: 9%	NA
Chowdhury et al.[83]		
190 proximal and distal RA specimens (5–6 mm in length)	Histologically normal RA •Proximal segments: 33% •Distal segments: 11.5%	Medial calcification and arteriosclerosis: history of smoking, diabetes, hypercholesterolemia, peripheral arterial disease, chronic renal failure
	Incidence of pathological changes in RA •Proximal segments: Intimal hyperplasia: 66.8% •Distal segments: intimal hyperplasia: 76.3%, medial calcification: 6.3%, arteriosclerosis: 5.8% Lesser degree of intimal hyperplasia and luminal narrowing in the proximal RA segments, $P < 0.001$	Intimal hyperplasia: Age >50 yr, smoking, hypertension
Ozkan et al.[82]		
312 RA specimens in patients undergoing heart surgery	Type I atherosclerosis: 49 specimens, 15% Type II atherosclerosis: 216 specimens, 70% Type III atherosclerosis: 16 specimens, 5% Type IV atherosclerosis: 7 specimens, 2% Type V atherosclerosis: 24 specimens, 8% Type VI atherosclerosis: 0 specimens Specimens with Grade ≥ III: 47 specimens, 16% Histological lesions I–VI as defined by the American Heart Association Committee on Vascular Lesions[71]	No significant predictors of RA atherosclerosis: age, gender, smoking, diabetes, peripheral vascular disease were not predictors of RA atherosclerosis

IMR = intima-to-media ratio.

harvest.[97,109–111] The major argument against the routine use of the Modified Allen's Test is the lack of evidence that it can predict hand ischemia after radial artery cannulation.[16,112,113] Slogoff et al.[16] evaluated the Modified Allen's Test in 411 cardiovascular surgical patients reporting that 3.9% of patients had a recovery time of >15 s. Despite this, radial artery cannulation was performed in these patients without ischemic complications. Abu-Omar et al.[109] reported radial artery harvesting without ischemic sequelae in 38 patients with an abnormal Modified Allen's Test but normal Doppler ultrasound results (zero incidence in a small number of patients does not preclude a considerable risk of ischemic complications[114]). Consistent with these findings are those of Barbeau et al.[102] who found that 80% of patients with an abnormal Modified Allen's Test scheduled for transradial cardiac instrumentation had adequate collateral perfusion on plethysmography and oximetry tests. Ghuran et al.[115] have even proposed that prescreening with the Modified Allen's Test in the presence of palpable radial pulse is not required, because they reported no ischemic sequelae in 630 patients who underwent 662 transradial coronary interventions without prescreening. Conversely, hand ischemia after radial artery cannulation has been reported despite a normal Modified Allen's Test before cannulation.[104,116–119] Mangano and Hickey[118] described development of progressive ischemic injury requiring amputation of the distal segments of 2 fingers in a patient with a normal Modified Allen's Test and uncomplicated perioperative course. The authors hypothesized that an embolic event was the mechanism for digit ischemia. The predictive value of a normal precannulation Modified Allen's Test was further questioned by Stead and Stirt[120] who reported that digital perfusion was independent from the palmar perfusion as measured by the Modified Allen's Test. Jarvis et al.[103] compared the Modified Allen's Test with Doppler ultrasound of the princeps pollicis artery in 93 hands of 47 patients before radial artery harvest and reported it to be a poor predictor of ulnar artery collateral flow. The diagnostic accuracy of the Modified Allen's Test, compared with ultrasound, was only 80%, with a sensitivity of 76% and a specificity of 82% occurring with a 5-s recovery time.[103] The authors concluded that the Modified Allen's Test was unable to identify a cutoff point for determining adequate collateral blood flow to the hand. Glavin and Jones[121] compared the Modified Allen's Test with Doppler ultrasound in 75 patients (150 extremities) finding the former to have a sensitivity of 87% to correctly diagnose the presence of ulnar artery blood flow and a negative predictive value of only 0.18; i.e., 80% of all abnormal Modified Allen's Test results in their study were incorrect.

Adjuncts to the Allen's Test

Pulse oximetry has been used with the Modified Allen's Test to make interpretation more objective[102,122–130] and less dependent on the patient's cooperation.[127,129,130] The time for the oxygen saturation (measured on the thumb or finger) to return to baseline after release of the occlusion is measured for each artery. However, this method has been found to overdiagnose normal hand circulation compared with the Modified Allen's Test[65,102,122,126] (Web Supplement Table 2, see Supplemental Digital Content 2, http://links.lww.com/AA/A31). Cheng et al.[122] reported that all patients with an indeterminate Modified Allen's Test had a normal test using pulse oximetry. However, because blood flows as low as 4%–9% of baseline are associated with normal pulse oximetry values, the demonstration of normal pulse oximetry saturation may not ensure adequate tissue perfusion.[131] Despite this theoretical concern,[65] the Modified Allen's Test using pulse oximetry has been used for selection of patients for radial artery harvest with no instances of vascular compromise in a series of 401 patients.[125]

The incorporation of plethysmography with the Modified Allen's Test allows visualization of pulsatile flow and more objective assessment of reperfusion.[132] Some consider it superior to pulse oximetry in evaluating the hand's collateral perfusion.[65] However, plethysmography suffers from the inability to quantify blood flow.[133]

The introduction of Doppler ultrasound in the assessment of collateral hand circulation allows for a comprehensive examination of the hand and forearm arteries[47,63–65,68,69,77,100,104,134,135] (Web Supplement Table 3, see Supplemental Digital Content 3, http://links.lww.com/AA/A32). A Doppler ultrasound examination consists of 2 parts. The first evaluates the "static" anatomy and flow of the arteries[77] and the second part incorporates the Modified Allen's Test with "dynamic" radial and ulnar artery compressions to assess the response of the collateral circulation.[68,69] It is performed with the Doppler ultrasound probe placed over the ulnar artery, radial artery, superior palmar arch, or dorsal digital thumb artery. There are no established standard criteria for Doppler ultrasound findings that define abnormal hand collateral perfusion. Accordingly, multiple definitions of inadequate collateral flow have been reported.[63,64,68,69,77,100,101,103,104,134,136] Finally, Ruengsakulrach et al.[68] suggested that no flow in the dorsal digital thumb artery with radial artery occlusion is the sole absolute contraindication for radial artery harvest.

Other tests for arterial collateral flow assessment of the hand include the "snuffbox test,"[136,137] "squirt test,"[138] postocclusive reactive circulatory hyperaemia test,[139] measurement of the systolic thumb pressure,[140–142] and the radial hyperemic response test.[143] Even magnetic resonance angiography has been suggested for preoperative evaluation of hand circulation.[144]

Together, the literature suggests that a normal Modified Allen's Test safely selects patients for radial artery harvest.[53,68,97,109–111,145–147] In contrast, there is no proof that the Modified Allen's Test can predict hand ischemia with radial artery cannulation.

ULNAR ARTERY CANNULATION

Few studies have addressed the use of the ulnar artery for invasive arterial blood pressure monitoring reporting a safety and efficacy profile similar to that for radial artery cannulation.[16,148–152] In a series of 50 patients, Karacalar et al.[151] described a 100% success rate of cannulation in patients with strong ulnar pulse and 59% success rate in patients with a weak ulnar pulse without complications.[151] Slogoff et al.[16] reported no hand ischemia in 22 patients who had an ulnar artery catheter placed after a failed radial artery cannulation. However, digital ischemia after ulnar artery cannulation after unsuccessful radial artery catheterization has been reported.[153] Hand ischemia has been reported in pediatric patients with prolonged ulnar artery cannulation in the setting of prior radial artery cannulation.[149] Although there is a theoretical concern that ulnar artery cannulation could cause neural trauma to the ulnar nerve, the literature lacks evidence of such a complication.[16,23,151,154–158] There is increasing interest in the use of the ulnar artery as an entry site for percutaneous coronary interventions when there are few other portal options.[23,154–157,159] This approach has been safely used in patients with adequate radial artery flow,[23,152,155,159] in those with compromised radial artery flow resulting from multiple punctures,[156,157] and in those with known chronic radial artery occlusion.[154] A randomized study of 431 patients found the transulnar approach for coronary angioplasty to be as safe and effective as the transradial artery approach.[152] Similar rates of access success (transulnar 93.1% vs transradial 95.5%), complications, and asymptomatic artery occlusions (transulnar 5.7% vs transradial 4.7%) were reported. Mangin et al.[157] evaluated the transulnar artery approach in 117 consecutive patients who underwent 122 percutaneous coronary interventions reporting puncture failure in only 9 of 122 attempts. Complications were noted in 7 patients (7.5%) including local (5 patients) or extended (1 patient) hematoma and false aneurysm (1 patient). The role of the Modified Allan's Test in risk stratification before cannulation of the ulnar artery is poorly defined.[154,156]

RADIAL ARTERY HARVEST

Radial artery harvest for coronary artery bypass graft surgery provides a model for examination of the effects of radial artery occlusion. Removal of the radial artery is associated with a significant increase in ulnar artery diameter and blood flow velocity.[160] Most investigators evaluating hand perfusion days to months after surgery using various methods (e.g., photoelectric plethysmography,[160] laser Doppler flowmeter,[161,162] venous occlusion plethysmography,[163] digital-brachial indices,[164] or pulsed wave Doppler[165]) have reported no significant decline in hand perfusion relative to the nonoperated hand (Web Supplement Table 4, see Supplemental Digital Content 4, http://links.lww.com/AA/A33). Early postoperative forearm blood flow has been reported to be similar to preoperative values during exercise-induced ischemic reperfusion.[163] In contrast, Lee et al.[166] reported a significant decline in digital blood flow 7 days after radial artery harvest. However, after 3 yr, blood flow increased to levels similar to those in the control arms.[167] The long-term effects of radial artery harvest were examined in a series of 34 asymptomatic patients by Serricchio et al.[168] who reported that ulnar artery peak systolic velocity was greater in the operated arm compared with the control arm 5 yr after radial artery harvest. Handgrip exercise stress led to a significant increase in ulnar artery diameter in both arms. Despite this increase, handgrip exercise was associated with a decrease in transcutaneous PaO_2 and an increase in transcutaneous $PaCO_2$ in the operated hand.[168] After 10 yr, a small degree of exercise-induced transcutaneous oxygen desaturation in the absence of symptoms was reported.[169,170] Long-term follow-up data[169,170] further suggest that the compensatory increase in ulnar artery blood flow after radial artery harvest may accelerate atherosclerosis (Fig. 3). Echo-Doppler evaluation performed in 39 patients 10 yr after radial artery harvest demonstrated greater intima-media thickness of the ulnar artery (Fig. 3), and a higher prevalence of atherosclerotic plaques compared with the nonoperated arm.[169]

A growing body of literature examining microsurgery of radial artery flap transfer supports the long-term safety of radial artery harvest.[171–175] Physiologic adaptation after radial artery harvest includes enlargement in the diameter of the remaining forearm arteries and a compensatory increase in blood flow velocity to the hand.[168,170,172,173] During rest, these adaptations usually provide adequate perfusion, but with exercise insufficient perfusion can occur.[169,168]

Although a rare event, the most feared complication of radial artery harvest is acute hand ischemia. Nunoo-Mensah[176] described a patient with acute hand ischemia despite a normal preharvest Modified Allen's Test, normal pulse oximetry saturation during intraoperative radial artery occlusion, and good backflow from the distal radial artery stump. The patient was subsequently found to have a congenital absence of the ulnar artery and a large interosseous artery. The patient underwent successful cephalic vein to distal radial artery revascularization. Three other patients have been described to have experienced hand ischemia after radial artery harvest. Tatoulis et al.[177] reported postoperative fingertip ischemia in 2 patients with scleroderma (0.08%) after radial artery harvest. Manabe et al.[104] described 1 patient who, despite a normal Modified Allen's Test, developed ischemia of the thumb several days after the operation.

COMPLICATIONS OF RADIAL ARTERY CANNULATION

The reported incidence of at least temporary radial artery occlusion after cannulation is between 1.5% and 88%.[178,179] In a review of 78 publications involving 19,617 cannulations, Scheer et al.[8] reported that the incidence of temporary radial artery occlusion was 19.7%. Temporary spasm can occur in up to 57% of radial arteries immediately after cannula insertion.[148] Thrombotic occlusion has been described as early as 2 h after radial artery catheter insertion or as late as a week after catheter removal.[16,180] In a study of 100 surgical patients undergoing radial artery cannulations, of which 40 developed radial artery occlusion, Bedford and Wollman[85] found that at the time of decannulation, only 42% of these 40 occlusions were present. Another 30% of all occlusions occurred within 24 h of decannulation and another 28% occurred later than 1 day after decannulation. Symptoms of radial artery occlusion can persist for several days after catheter removal.[16,181] Davis and Stewart,[14] using Doppler ultrasound, reported a 24% incidence of complete occlusion 8 days after decannulation. Recannulation of an occluded radial artery as late as 75 days after catheter removal has been reported.[85]

Digital embolization, a major source of hand ischemia with radial artery cannulation,[16,118,182,183] can lead to irreversible digital ischemia even in a setting of macroscopically and microscopically normal radial, ulnar, and superficial palmar arteries.[183] Downs et al.,[180] in a study of 32 patients, reported

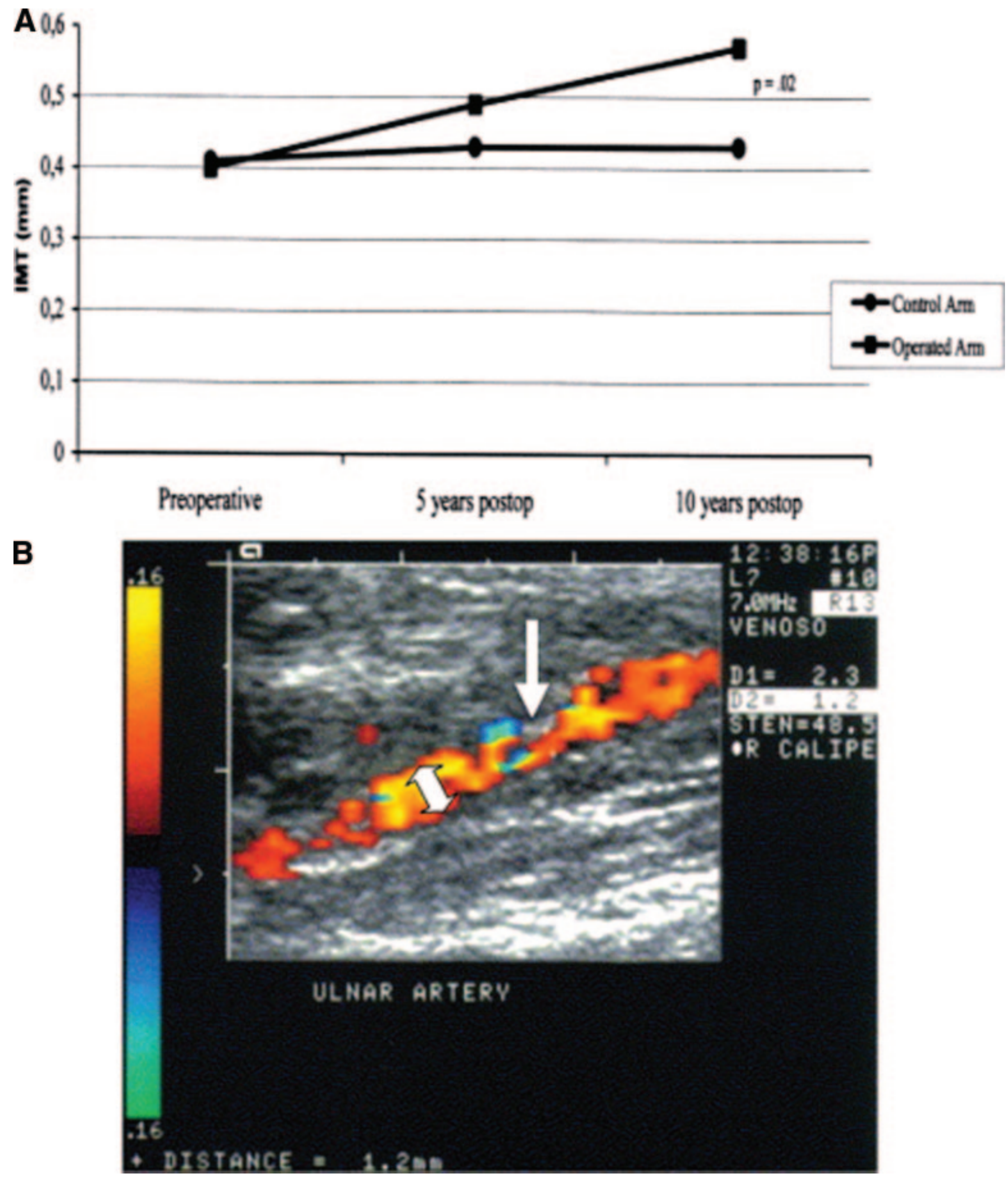

Figure 3. Changes of the ulnar artery (UA) intima-media thickness (IMT) 10 yr after radial artery harvest. A, Variations of IMT with time in the operated versus control arm. There was an increase in IMT of the UA on the operated hand that reached statistical significance at 10-yr follow-up. B, In addition to changes in IMT, the UAs on the operated side demonstrated a significantly higher prevalence of atherosclerotic plaques ($P = 0.03$). This color Doppler echocardiographic picture shows turbulent flow in the UA, irregular artery wall, and atherosclerotic plaques in the UA of the operated arm 10 yr after surgical intervention marked by a white arrow. The white double arrow marks the radial artery lumen. (Reproduced from Gaudino et al.[170] with permission.)

thrombotic embolization in 23% of patients after radial artery cannulation. Multiple emboli were seen not only in the radial artery but also in the other major arteries of the upper extremity including the brachial, ulnar, and interosseous arteries.[180] Rapid manual "flushing" of an indwelling radial artery catheter has been found to produce retrograde flow in the brachial and axillary arteries on duplex ultrasound examination.[184] Cerebral air embolization associated with manual flushing of a radial artery catheter[185,186] is, however, a rare event.[187] It has been suggested that local injury induced by an indwelling radial artery catheter, together with radial artery constriction at the time of decannulation, can promote thrombus formation.[85]

There are multiple reports of severe hand ischemia associated with radial artery cannulation.[180–182,188–191] In the review by Scheer et al.,[8] the incidence of permanent hand ischemic damage was 0.09%. However, the incidence of hand ischemia after radial artery cannulation is difficult to estimate because most cases are probably not reported. Hand ischemia requiring amputation as late as 10 days after decannulation has been reported.[119]

Other complications of radial artery cannulation include sepsis (0.13%), local infection (0.72%), pseudoaneurysm (0.09%), hematoma (14.4%), bleeding (0.5%), and skin necrosis proximal to the site of cannulation.[8,192] It has been suggested that hyperextension of the wrist results in impairment of median nerve function.[18,193] Data on the frequency of arterial catheter-related infections are inconsistent.[194] Catheter-related bacterial colonization is reported to range from <1% to 22.5%.[195–206] There is controversy as to whether radial artery cannulation is associated with a decreased incidence of infections compared with femoral artery cannulation.[195,196,198,202,203,205,207] It is also unclear whether there is an increased risk of infection with increasing duration of the cannulation.[196,201,204,205] A recent prospective study reported that arterial cannulation was associated with less than half the incidence of catheter-related bloodstream infection compared with central venous catheterization (0.92 [95% confidence interval {CI}, 0.13–6.44] vs 2.23 [95% CI, 1.12–4.44] per 1000 catheter days, respectively).[205] However, both sites had the same incidence of catheter colonization (15.71 [95% CI, 9.5–25.9] vs 16.83 [95% CI, 13.3–21.3] per 1000 catheter days, respectively),[205] emphasizing the importance of the arterial cannulation site as a potential source of sepsis.[194,208] However, current guidelines from the Centers for Disease Control and Prevention[209] and others[194,205] do not recommend routine replacement of peripheral arterial catheters at fixed intervals to prevent infections. Immunocompromised patients, however, may benefit from routine catheter change every 4 days.[201] An aseptic technique for radial artery catheter placement that includes skin cleansing with an antiseptic alcohol containing chlorhexidine solution is recommended.[209,210] Maximal barrier precautions did not, however, reduce the risk of arterial catheter-related bloodstream infection in a randomized study.[211]

RISK FACTORS FOR ISCHEMIC HAND INJURY WITH RADIAL ARTERY CANNULATION

There remains considerable controversy over reliable predictors of radial artery occlusion and ischemic hand injury after direct cannulation.[14,16,17,148,212,213] In a seminal study of 1699 patients from the Texas Heart Institute, Slogoff et al.[16] were unable to identify any predictors of serious ischemic complications of direct radial artery blood pressure monitoring. However, analysis of the aggregate literature suggests that a combination of profound circulatory failure, hypotension, and high-dose vasopressor therapy may increase the risk of hand ischemia[16,182,188,190,214] (Table 6). Signs of multiple digital emboli have been frequently reported in such instances.[16,85,183,214,217] Hematoma at the puncture site has been associated with an increased incidence of occlusion.[14,16,17,212] Other factors reported to be associated with radial artery injury are more controversial such as the number of puncture attempts,[14,16] artery size,[16,85,105,213,215] the composition of the catheter (teflon versus polypropylene),[14,16,148,178,180,213,215,216] catheter diameter,[16,85,105,213,215] the duration of cannulation,[14,16,85,148,218,219] and gender.[17,148] The method of puncture (direct puncture versus transfixation technique) has been reported to have no effect on risk for thrombosis,[17,212] and recannulation of previously cannulated radial arteries did not increase the frequency of occlusions.[14] The use of large sheaths (5F or 6F) for cannulation, as used in transradial coronary interventions, has been associated with vessel narrowing, occlusion, and subsequent failure to cannulate the radial artery.[220] Finally, longer catheters (>2 inches) were associated with higher catheter patency[221] and fewer incidences of occlusion after decannulation compared with shorter catheters (≤2 inches).[222]

Table 6. Risk Factor Assessment Before Radial Artery Catheter Placement

Risk of hand ischemia may be elevated in patients with following risk factors
Patient-related risks[16,105,148,176,177,213]
Documented incomplete hand collateralization
Other anatomical limitations, e.g., mall radial artery diameter; documented anatomical variation, e.g., absent ulnar artery
Preexisting atherosclerosis, e.g., lderly diabetic smoker with peripheral artery disease
Disease states, e.g., patients with scleroderma, Raynaud's disease
Catheter and placement technique related risks[14,16,17,212]
Inexperienced operator
Hematoma at the puncture site
Vasospasm of the radial artery precipitated by manipulation of the of the catheter
Surgery and hospital course-related risks factors[16,182,188,190,214]
Anticipated need for prolonged arterial cannulation
High risk for profound circulatory failure
High risk for prolonged perioperative hypotension
Anticipated need for prolonged or high-dose vasopressors therapy
High risk for thrombosis and/or digital emboli, e.g., patient with a contraindication to heparin flush solution, patient with preoperative hypercoagulable state
Factors that have a limited or conflicting evidence for increasing the risk of hand ischemia
Number of puncture attempts[14,16]
Large indwelling catheters (>20 guage)[16,85,105,213,215]
Polypropylene catheter (in comparison to teflon catheter)[14,16,148,178,180,213,215,216]
Female gender[17,148]
Infiltration of local anesthetics around the radial artery precipitating vasospasm[148]
Factors not associated with increased frequency of radial artery occlusion
Transfixation cannulation technique (in comparison to direct puncture cannulation technique)[17,212]
Recannulation of previously cannulated radial artery[14]
Reversing the direction of the cannula[148]

A plethora of patient-specific (e.g., atherosclerosis), cannulation-related (e.g., thrombosis, vasospasm, emboli), and hospital course–related (e.g., hypotension, vasopressors) risk factors emphasizes the multifactorial nature of ischemic complications of indwelling radial artery cannulation making precannulation risk assessment challenging (Table 6).[182] Any of these risk factors might override compensatory mechanisms protecting hand perfusion leading to ischemia despite adequate precannulation hand collateralization.[182] Whether ultrasound-guided arterial cannulation can improve outcomes from radial artery cannulation is not yet clearly established.[223–228] Tables 6 and 7 provide a summary of risk factor assessment before radial artery cannulation (Table 6) and an algorithm for avoiding catheter-associated complications (Table 7).

HEPARIN VERSUS NONHEPARIN FLUSH SOLUTIONS FOR MAINTAINING ARTERIAL CATHETER PATENCY

Much debate has centered around the most appropriate solution for maintaining the patency of

Table 7. Algorithm for Minimizing Catheter Associated Complications in Patients with Multiple Risk Factors for Hand Ischemia[8,16,17,85,188,218,221,229]

Reconsider the necessity for invasive monitoring.
Perform Doppler ultrasound exam for detailed anatomy assessment and dynamic blood flow exam.
Consider alternative sites for arterial cannulation, e.g., dorsal radial artery,[260] femoral,[8,195] dorsalis pedis,[229,230] and axillary arteries.[8] The limited data on use of brachial artery cannulation suggests that it can be considered in adults,[195,231–233] neonates, and small children.[226,234]
Minimize trauma associated with placement, e.g., perform real-time ultrasound examination, discontinue temporarily any anticoagulation treatment to decrease the risk of bleeding, and hematoma.[14,16,17,212]
Limit the duration of monitoring.[218]
Routine use of Modified Allen's Test has not been demonstrated to predict ischemic complications with the exception of patients undergoing radial artery harvest.[115,121]
Consider use of heparinized flush solution if the radial artery catheter is required for longer than 24 h.

arterial catheters during continuous blood pressure monitoring. Heparinized solutions are considered advantageous by some investigations, but heparin exposure might promote antibody formation leading to heparin-induced thrombocytopenia.[235–237] Continuous heparin flush solution has been reported to affect coagulation studies if drawn via arterial access.[238–241]

Several randomized controlled trials have compared heparin with nonheparinized solutions for maintaining arterial catheter patency[221,238,242–244] (Table 8). The American Association of Critical-Care Nurses' multicenter, randomized, controlled trial involving 5139 intensive care unit (ICU) patients at 198 sites found heparin superior for maintaining catheter patency compared with nonheparinized solutions.[221] The data were collected at 4-h intervals for up to 72–96 h, or until the removal of the catheter.[221] Of note, catheter insertion depth >2 inches, male gender, femoral cannulation site, and use of other anticoagulants or thrombolytics were identified to enhance arterial catheter patency.[221] Other smaller studies performed in the ICU setting found no superiority,[238] a trend toward superiority,[243] or superiority[242] with heparin- versus nonheparin-containing solutions. In patients requiring arterial catheter during the perioperative period, a randomized, controlled, double-blind trial in 200 patients failed to demonstrate any significant difference in the number of radial artery occlusions between heparinized catheter flush solution compared with normal saline.[244] The optimal heparin concentrations have not been established, with the heparin concentrations used ranging from 1,[238,244] 2,[243] 4,[242] and 5 U/mL.[245] A study comparing 2 heparin concentrations, 0.25 and 1 U/mL, failed to demonstrate a significant difference in arterial catheter patency, suggesting that a low concentration is adequate in the adult population.[246] In contrast, Butt et al.[245] reported that a heparin concentration of 5 U/mL (154 catheters) led to prolonged catheter patency compared with 1 U/mL (164 catheters) in children admitted to the ICU.

Table 8. Use of Heparin Versus Nonheparin Flush Solutions for Continuous Arterial Monitoring

Author	Number of patients and patient setting	Heparin concentration	Patency of the arterial catheter over time (h)	Conclusion
Clifton et al.[242]	30 medical ICU	4 U/mL	After: 40 h/96 h Heparin: 100%/86% Nonheparin: 52%/52%	Heparin is superior ($P < 0.05$)
American Association of Critical-Care Nurses Thunder Project[221]	5139 ICU	Variable	After: 24 h/48 h/72 h Heparin: 97%/94%/90% Nonheparin: 93%/86%/90%	Heparin is superior ($P < 0.00005$)
Kulkarni et al.[243]	78 surgical ICU	2 U/mL	After: 73 h/96 h Heparin: 92%/92% Nonheparin: 84%/74%	Nonsignificant trend toward a superiority with heparin containing flush solution ($P = 0.06$)
Tuncali et al.[244]	200 operating room	1 U/mL	During the perioperative radial artery cannulation (5–9 h)/ after decannulation Heparin: 100%/94% (14% with partial occlusion) Nonheparin: 100%/98% (14% with partial occlusion)	No difference between the heparinized and nonheparinized flush solution. The authors suggested elimination of heparin as a flush solution when the catheters are placed in adults for short-term intraoperative monitoring

ICU = intensive care unit.

Table 9. Clinical Reports on Characteristics, Treatment Options, and Outcome of Ischemic Complications of Radial Artery Catheterization (RAC)[a]

Author	Patients, sex/age	MAT	Reason for placement of RAC	Risk factors	Duration of RAC	Onset of ischemia	Diagnosis	Treatment	Outcome
Baker et al.[190]	F/90	Equivocal	Appendectomy	Hypotension vasopressor	6 d	7 d	All 5 patients had thrombi	Fluids, heparin	Amputation, digit 3
	M/52	Normal	Intestinal surgery		56 h	40 h		Dextran-40, heparin, sympathetic block, thrombectomy	Amputation, digit 1–5
	M/59	NA	Intestinal surgery		48 h	48 h		Dextran-40, heparin, reserpine	Amputation, digit 1–2
	M/68	Normal	Pancreas cancer		78 h	72 h		Dextran-40, heparin, sympathetic block	Amputation, digit 1–2
	M/74	Normal	Major vascular		29 h	28 h		Dextran-40, heparin, sympathetic block	Cold sensitivity, digit 1–3
Crossland and Neviaser [247]	10 patients	Normal	Not specified	NA	NA	NA	Thrombosis	Cannula removal	Recovery in 10 patients
Total of 600 RAC. Sixty patients developed hand ischemia (incidence of 10%)	50 patients	NA	Not specified		NA	NA		45 patients needed surgical exploration	Recovery in 37 patients Amputation in 13 patients
Burrell[248]	F/57	NA	Cardio-respiratory arrest	NA	24 h	10 h after decannulation	Vasospasm	Intraarterial diluted solution of phentolamine	Recovery
Arthurs[116]	M/78	Normal	Femoral aneurysm repair	Hypotension		7 d after cannulation		None	Recovery over 2 wk
Mangano and Hickey[118]	M/54	Normal	CABG	None		24 h		Axillary block, surgical exploration	Digital amputation
Gallacher[117]	M/67	Normal	Left lower lobectomy	Raynaud's	Intraoperative period	Immediately postoperatively		Intraarterial verapamil 1 mg	Recovery
Sarma[249]	M/54	[a]	AAA repair	Hypotension	Intraoperative period	Immediately postoperatively		Intraarterial prilocaine 25 mg	Recovery
Mangar et al.[119]	M/35	Equivocal	Femoral-tibial bypass	None		10 d postoperatively		Anticoagulation	Limb amputation
Bright et al.[250]	F/14	NA	Tetralogy of Fallot repair	Low CO		Within 12 h postoperatively		Axillary block, thrombectomy	Limb amputation
Lee et al.[183]	M/46	NA	Septic shock	Hypotension vasopressors	8 h	8 h	Complete occlusion of all common digital arteries (thrombus versus embolus)	Intraarterial papaverine Cannula removal Dextran-40, nitroglycerine patch	Gangrene/death
Lee et al.[217]	M/48	Normal	Spine surgery	None	Intraoperative period	8 d	Thrombus	Surgical exploration Postoperatively: heparin, Dextran-40	Recovery
Scheer et al.[8] Review of 78 studies with a total of 19,617 RAC. Four patients developed hand ischemia (incidence of 0.09%)	4/19,617 patients (0.09%)								Permanent ischemic damage
English et al.[251]	M/14	NA	Spine fusion	Hypotension	Intraoperative period	Immediately postoperatively		Warm compresses	Immediate resolution
Geschwind et al.[214]	M/59	NA	NA	2 patients received vasopressors	NA	Time interval from decannulation to the initiation of thrombolytic therapy averaged 6 d (2–12 d)	Vasospasm in 2 patients	Catheter-directed thrombolytic infusion of Urokinase	Recovery
Total of 7000 RAC (incidence of thrombolytic therapy 0.1%)	F/46			Several had history of vascular disease			All 7 had a combination of thrombi and emboli	The dose ranged between 570,000 IU and 5,900,000 IU	Amputation
The total number of patients with hand ischemia was not provided	F/49 F/41 F/65 M/62 M/54								Recovery Failure Recovery Recovery Recovery

(*Continued*)

Table 9. Continued

Author	Patients, sex/age	MAT	Reason for placement of RAC	Risk factors	Duration of RAC	Onset of ischemia	Diagnosis	Treatment	Outcome
Valentine et al.[182]	8 patients (estimated incidence: 0.01%)	NA	CABG × 2, pulmonary resection × 2, craniotomy, mesenteric bypass, carotid endarterectomy, strangulated hernia	Diabetes mellitus, smoking, coronary artery disease	1 d ($n = 2$)	NA	Emboli, thrombi, and vasospasm	Thrombectomy with patch angioplasty ($n = 4$)	Death ($n = 1$)
					2 d ($n = 2$)			Thrombectomy with vein graft interposition ($n = 1$)	Digit gangrene ($n = 3$)
					3 d ($n = 1$)			Observation ($n = 1$)	Digit gangrene
					6 d ($n = 1$)			Oral nifedipine ($n = 1$)	Digit gangrene
					9 d ($n = 1$)			Intraarterial verapamil with intravenous heparin ($n = 1$)	Pain, cold intolerance
					14 d ($n = 1$)				Asymptomatic

CABG = coronary artery bypass graft; AAA = abdominal aortic aneurysm; CO = cardiac output; NA = not applicable.

[a] The first column lists the authors and the total number of patients, if provided. In most of those retrospective reports, however, the total number of all radial artery cannulation is not available, and only patients with hand ischemia are described. The second column lists the sex (male or female) and the ages of each individual patient, who suffered from ischemic complication. The third column describes the results of the precannulation Modified Allen's Test (MAT). The following columns summarize the reasons for placements, potential risk factors for development of hand ischemia, duration of the radial artery cannulation, and the time of onset of ischemia after placement of the cannula. The column "Diagnosis" summarizes what the original authors thought is the most likely underlying etiology of the ischemia.

TREATMENT OF ISCHEMIC COMPLICATIONS

There is no consensus on the optimal treatment for ischemic injuries resulting from radial artery cannulation (Table 9). Early recognition is likely the most important means to reduce permanent injury. An absent pulse, dampened waveform, blanched or mottled skin, delayed capillary refill, and painful and cold hand or fingers with motor weakness are presentations of hand ischemia.[182,190,214] Blistering and skin ulceration are late findings.

Arterial color flow Doppler ultrasound, angiography, or magnetic resonance imaging can be used to evaluate arterial flow in the arteries of the affected limb. Doppler ultrasound examination has the advantage of being noninvasive and easily performed, but it is limited by the inability to identify the mechanism of compromised blood flow. Immediate consultation with a vascular surgeon is imperative.[183,217] The radial artery catheter should be removed to ensure that it is not contributing to flow obstruction if intraarterial drug administration or arteriography is not under consideration.

Treatment is aimed at the underlying mechanism (e.g., radial artery thrombus, ulnar artery or radial artery vasospasm, local radial artery trauma, reduced systemic arterial perfusion, digital embolization, or previously unrecognized congenital inadequate collateral hand circulation). Different management techniques for radial artery occlusion have been attempted and are summarized in Table 9.[116–119,182,188–190,249–251] Aspiration of the thrombus at the catheter tip has been described to restore arterial pulsation in 60% of patients with suspected thrombosis.[195] Intraarterial verapamil, prilocaine, and phentolamine have been successful to reverse ischemic symptoms.[117,118,195,248,250] Other proposed treatments include low-molecular-weight dextran and low-dose heparin.[182,183,190] Geschwind et al.[214] reported angiographic flow restoration with <20% residual thrombus leading to clinical improvement in 5 of 7 patients treated with intraarterial urokinase for radial artery occlusion due to thrombosis.

Hot compresses to the involved extremity may resolve vasospasm[251] (but could aggravate the ischemia if applied to the hand). Sympathetic nerve block[14,252] or cervicodorsal sympathetic block[190] should be considered for suspected arterial vasospasm.[14,188,190,252,253] There is a growing body of literature on prevention and management of radial artery spasm during transradial artery cardiac catheterization demonstrating that intraarterially administered vasodilators (e.g., nitrates, calcium channel blockers, lidocaine, and molsidomine) are safe and effective in preventing radial artery spasm.[254–256] Radial artery spasm after an initial failed attempt can be reversed with subcutaneously administered nitroglycerin alone[257] or in combination with 2% lidocaine.[258]

Surgical exploration is often necessary for patients with absent radial artery blood flow and severe hand ischemia as a complication of radial artery cannulation. Despite successful cases being reported, operative therapy has not been conclusively demonstrated to be superior to medical therapy.[217,247] In a retrospective analysis of treatment of 8 patients with hand ischemia after radial artery cannulation, surgical revascularization was attempted in 5 patients.[182] Of the 5, 1 patient died; all patients who survived developed gangrene of the first or second digit, with 2 patients requiring finger amputation. In contrast, only 1 of 3 patients treated conservatively developed gangrene and underwent amputation.[182] Unsuccessful surgical exploration has been reported by others.[118]

Note added in proof: A crucial reference (Pyles et al.[260]) originally published by *Anesthesia & Analgesia* was added during the proof review process.

ACKNOWLEDGMENTS

The authors acknowledge the administrative and editorial assistance of John Rukkila, ELS.

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