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STATE-OF-THE-ART REVIEW

Best Practices for the Prevention of Radial Artery Occlusion After Transradial Diagnostic Angiography and Intervention

An International Consensus Paper

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ABSTRACT

Transradial access (TRA) is increasingly used worldwide for percutaneous interventional procedures and associated with lower bleeding and vascular complications than transfemoral artery access. Radial artery occlusion (RAO) is the most frequent post-procedural complication of TRA, restricting the use of the same radial artery for future procedures and as a conduit for coronary artery bypass graft. The authors review recent advances in the prevention of RAO following percutaneous TRA diagnostic or interventional procedures. Based on the available data, the authors provide easily applicable and effective recommendations to prevent periprocedural RAO and maximize the chances of access in case of repeat catheterization or coronary artery bypass grafting surgery. (J Am Coll Cardiol Intv 2019;12:2235–46)

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ABBREVIATIONS AND ACRONYMS

ACS = acute coronary syndrome

CABG = coronary artery bypass grafting

OD = outer diameter

RAO = radial artery occlusion

TR = transradial

TRA = transradial access

UFH = unfractionated heparin

Transradial access (TRA) is increasingly used for diagnostic and interventional procedures, becoming the preferred vascular access route in most countries. This is mainly driven by the large body of evidence from observational studies and large randomized trials demonstrating that TRA is associated with not only a reduced risk for access-site bleeding and vascular complications, but also reduced mortality in high-risk patient subgroups, such as those presenting with acute coronary syndromes (ACS) (1,2). This has led the European Society of Cardiology to recommend TRA over transfemoral access as a Class IA indication for patients with ACS undergoing invasive management, if performed by experienced radial operators (3). Similarly, a recent American Heart Association statement has proposed that TRA should become the default access site in patients with ACS in the United States (4).

Radial artery occlusion (RAO) is the most frequent post-procedural complication of TRA. Although asymptomatic from an ischemia standpoint in the vast majority of cases, it precludes ipsilateral TRA for future procedures. In particular, high bleeding risk patients might be denied the benefits of radial access in case of repeat procedures and radial arterial conduit might not be usable in case of referral for coronary artery bypass grafting (CABG) surgery. Recent evidence has suggested clinical benefit for the use of radial conduits over standard saphenous vein grafts (5) and the 2018 European Society of Cardiology/European Association for Cardio-Thoracic Surgery guidelines recommend the use of the radial artery (Class IB) for CABG (6). RAO will also restrict the use of the radial artery for arteriovenous fistula creation in patients requiring hemodialysis.

Therefore, prevention of RAO is of utmost clinical importance and should be a central consideration (7). However, the "real-world" incidence of RAO reported from experienced radial centers remains high (8), with wide variability in the uptake of RAO prevention strategies (9,10). In this paper, we provide guidance for the prevention of RAO based on the best current evidence.

HIGHLIGHTS

- RAO remains the most frequent post-procedural complication of transradial access, restricting the use of the same radial artery for future procedures, as a conduit for coronary artery bypass grafting or for arteriovenous fistula creation in patients requiring hemodialysis.
- The real-world reported incidence of RAO remains high, with wide variability in the uptake of RAO prevention strategies.
- The paper reviews the main recent advances in the field of RAO prevention and provides a series of expert recommendations to prevent RAO.
- This consensus document is meant to provide guidance to increase the adoption of simple and effective methods to achieve an institutional rate of RAO <5%, as demonstrated in the most recent large randomized trials.

METHODS

WRITING PANEL. The Radialist Alliance against Occlusion (RAO) international group was an initiative from 17 interventional cardiologists, all experts in radial artery access, and a cardiac surgeon with large experience in using radial conduits for CABG. All members agreed to review the best available and contemporary evidence and to provide a consensus document on best practices to prevent RAO. The writing of this document was motivated by the availability of recent major publications in the field of RAO prevention and the current lack of worldwide application of these preventive strategies. Recommendations were drafted when general agreement among authors was reached.

IMPORTANCE OF RAO: UPDATED EVIDENCE. In 2016, a systematic review and meta-analysis was completed and reported RAO rates using different methods and at different time intervals (8). From 1996 to 2015, a total of 66 studies with 31,345 participants were included in the analysis. The reported incidence of RAO ranged from <1% up to 33% and varied with timing and methods of assessment of radial artery patency. The overall incidence of early (within 24 h) RAO was 7.7%, which decreased to 5.5% (a ~30% reduction) at >1-week follow-up. When considering only randomized clinical trials from this meta-analysis (5,258 patients from 12 trials), the early RAO rate was still 7.7%.

We performed an updated search of relevant randomized studies assessing early RAO after TRA with the PubMed database through February 2019 to supplement the recent meta-analysis. We included several moderate- to large-sized randomized trials,

TABLE 1 Recent Randomized Trials Assessing Early RAO Rates

Year	First Author or Trial Name (Ref. #)	Study Protocol: Experimental vs. Reference Arm	Procedures	Patients	Overall Early RAO Rate (%)	Early RAO Rate, Experimental vs. Reference Arm (%)	P Value
2015	Dharma (27)	Post-procedural pre-hemostasis intra-arterial nitrates vs. placebo	Diagnostic/PCI	1,706	9.90	8.3 vs. 11.7	0.006
2016	PROPHET 2/Pancholy (42)	Patent hemostasis and prophylactic ulnar compression vs. patent hemostasis alone	Diagnostic	3,000	2.66	1.0 vs. 4.3	0.0001
2017	RAP and BEAT/Aminian (18)	6-F thin-walled sheath vs. 5-F standard sheath*	Diagnostic/PCI	1,836	2.61	3.47 vs. 1.74	NS*
2017	CRASOC 3/Dangoisse (26)	TR-Band with 10 ml of air and 1h30 compression vs. 10 ml of air and 2h compression	Diagnostic/PCI	736	2.44	2.3 vs. 2.8	NS
2017	PRACTICAL/Lavi (47)	Ultrashort (20 min) vs. short (60 min) compression with patent hemostasis	Diagnostic	568	3.87	4.9 vs. 2.8	NS
2017	Horie (37)	6.5-F sheathless guiding catheter vs. 6-F thin-walled sheath	PCI	600	0.80	0.0 vs. 1.7	NS
2018	MEMORY/Petroglou (57)	Manual vs. mechanical patent compression	Diagnostic	589	9.80	12.0 vs. 8.0	NS
2018	Chen (31)	Pre-puncture subcutaneous nitrates vs. placebo	Diagnostic	182	9.90	5.4 vs. 14.4	0.04
2018	Sanghvi (58)	TR-Band vs. Safeguard radial	Diagnostic/PCI	320	5.0	3.80 vs. 6.28	0.05
2018	SPIRIT OF ARTEMIS/Hahalis (21)	High vs. standard heparin dose	Diagnostic	1,836	5.60	3.0 vs. 8.1	<0.001
2018	STAT/Seto (46)	Hemostatic patch and TR-Band vs. TR-Band alone	Diagnostic/PCI	180	1.10	2.15 vs. 0.00	NS

Except the study of Dharma et al. (27), all studies were published after the Rashid et al. (8) meta-analysis. *Noninferiority design.

CRASOC = Compression of Radial ArterieS without Occlusion; MEMORY = Manual vErsus Mechanical cOmpression of the Radial arterY after transradial coronary angiography; NS = not significant; PCI = percutaneous coronary intervention; PRACTICAL = The Postcath Radial Arterial Clamp Time In the CAth Lab; PROPHET 2 = PROPhylactic Hyperperfusion Evaluation Trial; RAO = radial artery occlusion; RAP and BEAT = Radial Artery Patency and Bleeding, Efficacy, Adverse event; SPIRIT of ARTEMIS = Studying the Priority of Anticoagulation to Prevent Arterial Occlusion After Forearm Angiographies; STAT = Statseal with TR Band assessment trial.

with a total inclusion of 9,847 patients, assessing different preventive strategies for RAO, with various reported incidence of early RAO (**Table 1**), but with an overall decrease in the RAO rate to 3.7%, emphasizing improvements in the prevention of RAO over time (**Central Illustration**).

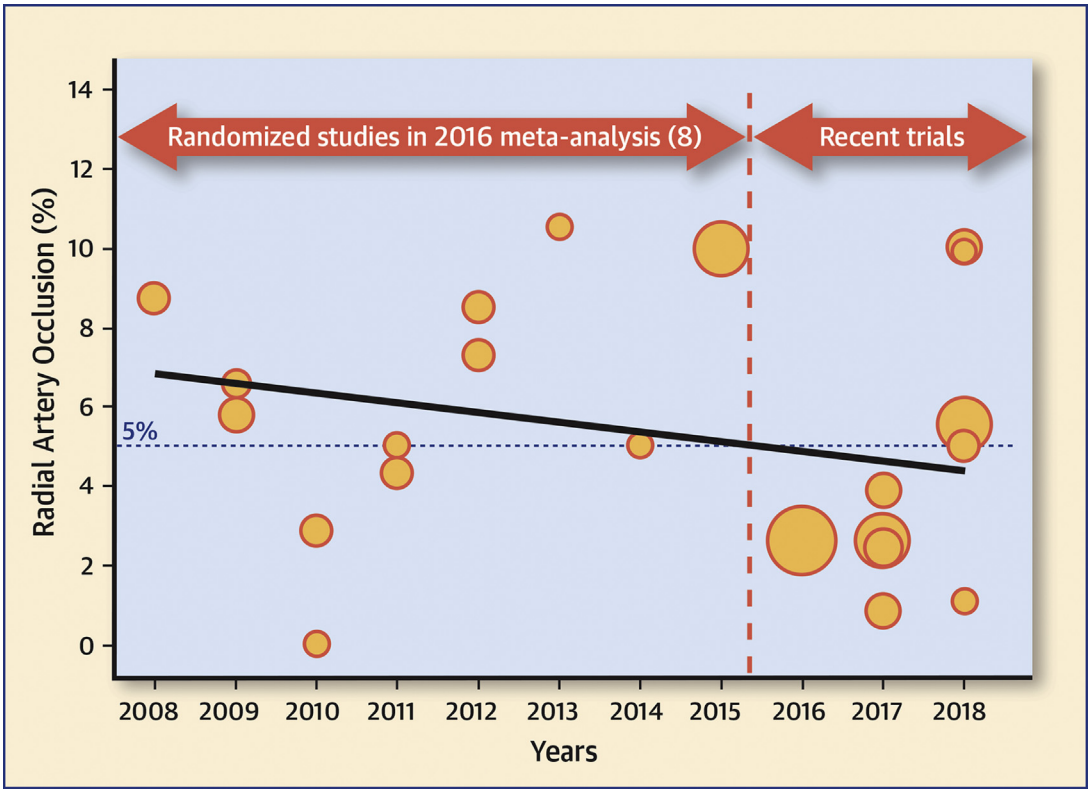
TIMING AND METHODS OF RAO DETECTION. According to a large international survey, routine assessment of radial artery patency before discharge remains largely suboptimal and performed by only 70% of operators, one-half of whom use simple palpation-based assessment of radial artery pulsation (9). Clinical estimation by radial pulse palpation is not recommended because it can lead to significant underestimation of RAO (11). Indeed, the distal stump of an occluded radial artery may have up to 70% of mean arterial pressure because of the palmar arch circulation or collateral arterial connections, with subsequent palpable radial pulse (12,13). The oximetry-plethysmography test provides a simple and inexpensive method of indirect evaluation of radial artery patency. Briefly, after placement of a digital sensor on the thumb, both radial and ulnar arteries are compressed transiently, with loss of oximetry-plethysmographic signal, after which the radial artery is released and the recovery of oximetry-plethysmographic signal while ulnar compression is maintained constitutes evidence of radial artery patency.

Ultrasound with Doppler assessment is also an important method for RAO detection, as it can provide not only accurate estimation of radial flow, but also important anatomical information such as the presence of arterial thrombus or dissections. In the absence of conclusive evidence for superiority of ultrasound with Doppler over oximetry-plethysmography, it is acceptable to use oximetry-plethysmography as the first method to detect RAO in routine clinical practice, due to its wide availability, ease of use, and limited cost, followed by ultrasound with Doppler to confirm RAO in patients with an abnormal oximetry-plethysmography test.

Importantly, reported rates of RAO are dependent on the timing of evaluation, with early RAO rates being significantly higher than rates assessed later (generally at 1 month). Late reopening of the radial artery has been reported from 10% to up to 65% (8). It is important to consider that "late" assessment of RAO after hospital discharge has generally been limited to study protocols and may not be achievable in routine practice. Therefore, we recommend performing early assessment of RAO (ideally within 24 h or before discharge) in all patients that undergo invasive procedures through the radial artery, with later assessment required only when RAO was initially present.

PATHOPHYSIOLOGY AND RISK FACTORS ASSOCIATED WITH RAO. Several studies using imaging or histological analyses of the radial artery have demonstrated significant structural changes after TRA catheterization (14,15). The primary mechanism of early RAO

CENTRAL ILLUSTRATION **Metaregression Analysis of Effects of Time on Early Radial Artery Occlusion in Randomized Trials From 2008 to 2018**



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The analysis shows a decrease in early RAO rates below 5% in 2018. Data are expressed as overall early RAO rates per studies. **Circles** represent each of the 22 studies included in the analysis.

after TRA consists of acute arterial thrombosis, resulting from the combined effect of catheter-related endothelial and vessel injury, local hypercoagulable state, and decreased blood flow from compressive hemostasis (7). Chronic RAO will develop in a sizeable proportion of these patients. Chronic RAO can also result from progressive intimal-medial thickening due to vascular smooth muscle proliferation and hyperplasia as a response to injury, secondary to repeat TRA (14,16).

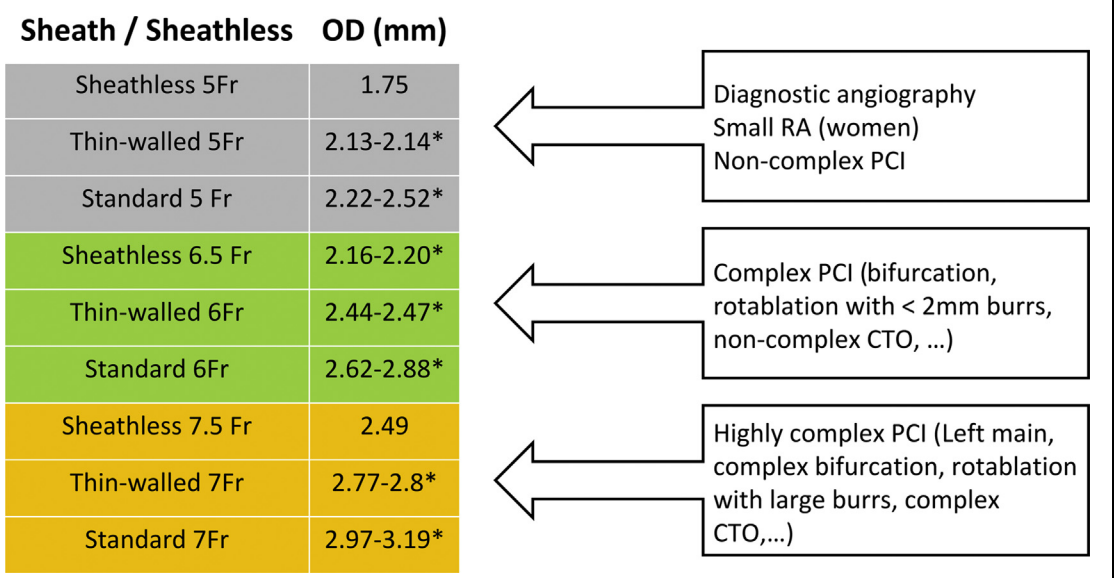
Risk factors associated with RAO are summarized in **Table 2**, and include modifiable and nonmodifiable risk factors. Among nonmodifiable risk factors, several baseline patient characteristics have been reported, including age, female sex, low body mass index, diabetes, ethnicity (South Asian origin), and previous radial artery access (16-19). Procedural risk factors include repeated unsuccessful attempts of radial punctures, increased sheath-to-artery ratio, lack of aspirin pre-treatment, and either no or low-dose periprocedural intravascular anticoagulation (16,18,20-22). Post-procedural risk factors include in particular occlusive ("nonpatent") hemostasis (19,23,24) and longer hemostasis time (25-28). The

TABLE 2 **Risk Factors for RAO**

Pre-procedural (nonmodifiable)	Female (17,19) Low BMI (19) Age (17,18) Diabetes (8) Previous radial artery access (16) Ethnicity (17,28)
Procedural (modifiable)	Insufficient anticoagulation (21) Sheath-to-artery ratio >1 (18,20) Repeated radial punctures (22) Spasm (21,27,31) Aspirin (18)
Post-procedural (modifiable)	Occlusive hemostasis (19,23,24) Prolonged hemostasis (26-28,45) Spasm (27)

BMI = body mass index; RAO = radial artery occlusion.

FIGURE 1 Recommendations for the Use of Current Sheaths and Sheathless Catheters According to Outer Diameters and Clinical Indications



*Variations in OD according to sheath/sheathless brands. CTO = chronic total occlusion; OD = outer diameters; PCI = percutaneous coronary intervention; RA = radial artery.

occurrence of radial artery spasm can further worsen endothelial injury by increasing friction between the radial artery and the sheath or catheter system. A recent large review on the effectiveness of intra-arterial vasodilators to reduce radial artery spasm found that verapamil at a dose of 5 mg or verapamil in combination with nitroglycerine (100 or 200 μg) are the best combinations to reduce spasm (29). The true impact of radial artery spasm on the occurrence of RAO has been less well defined (30), although 2 recent placebo-controlled randomized studies have demonstrated that subcutaneous "pre-puncture" or post-procedural "pre-hemostasis" intra-arterial injection of nitroglycerin was associated with a reduced incidence of RAO (27,31). Although randomized data have demonstrated that ultrasound guidance improves the success rate of radial artery cannulation, it is not yet known whether routine ultrasound guidance can result in lower incidence of RAO (32).

KEY PREVENTIVE STRATEGIES TO REDUCE THE OCCURRENCE OF RAO

IMPORTANCE OF MINIMIZING RADIAL ARTERY INJURY BY REDUCTION IN SHEATH AND CATHETER SIZE. In contrast to the femoral artery, the smaller size of the radial artery requires caution when using larger vascular sheaths and catheters. It is well recognized that using a sheath with an outer diameter (OD) larger than the inner diameter of the radial artery will promote vascular wall stretch and injury, but also blood flow reduction, endothelial dysfunction, and chronic remodeling, resulting in an increased risk of RAO (14,18,20,33). Rashid et al. (8) have evaluated the incidence of RAO by sheath size among 19 studies and found higher rates of RAO with increasing sheath sizes. Indeed, the incidence of RAO was found to be 0% in 1 study using 4-F sheaths, 2% in studies using 5-F sheaths, and rising to 11% and as high as 19.5% in studies using 6-F and 7-F sheaths, respectively (8). To overcome the inherent physical size limitations of the radial artery and to reduce the occurrence and importance of the sheath-to-artery mismatch, radial operators and the industry have developed and promoted miniaturization of transradial (TR) equipment by using either thin-walled sheaths or sheathless approaches (34–36).

In the large randomized international RAP and BEAT (Radial Artery Patency and Bleeding, Efficacy, Adverse event) trial, investigators compared a 6-F thin-walled sheath (OD of 2.45 mm) to a standard 5-F sheath (OD of 2.28 mm). Although the use of the 6-F thin-walled sheath was associated with one of the lowest reported rates of RAO for a 6-F compatible sheath, noninferiority against the standard 5-F sheath could not be demonstrated (3.47% vs. 1.7%; p for

TABLE 3 Patent Hemostasis Steps as Described in PROPHET and PROPHET II Trials (19,42)

1. Remove the arterial sheath 2–3 cm
2. Place the hemostatic compression device 2–3 mm proximal to the skin entry site, and tighten it or inflate it, to allow for sheath removal
3. Lower the compression pressure until some bleeding is visible
4. Reincrease the hemostatic pressure at a level just enough to maintain hemostasis
5. Assess radial artery patency by using the reverse Barbeau's test: Place the plethysmographic sensor on the index finger of the involved upper extremity with the observation of pulsatile waveforms Then, compress the ulnar artery at the level of the wrist, and observe the behavior of the waveform Absence of plethysmographic waveform will be indicative of occlusive compression In case of occlusive compression of the radial artery, gradual deflation/decompression of the hemostatic device should be performed until the plethysmographic signal returned, confirming radial artery patency

PROPHET = Prevention of Radial Artery Occlusion—Patent Hemostasis Evaluation Trial; PROPHET II = PROPhylactic Hyperperfusion Evaluation Trial.

noninferiority = 0.150), emphasizing again the impact of even a small increase in sheath OD on the occurrence of RAO (33).

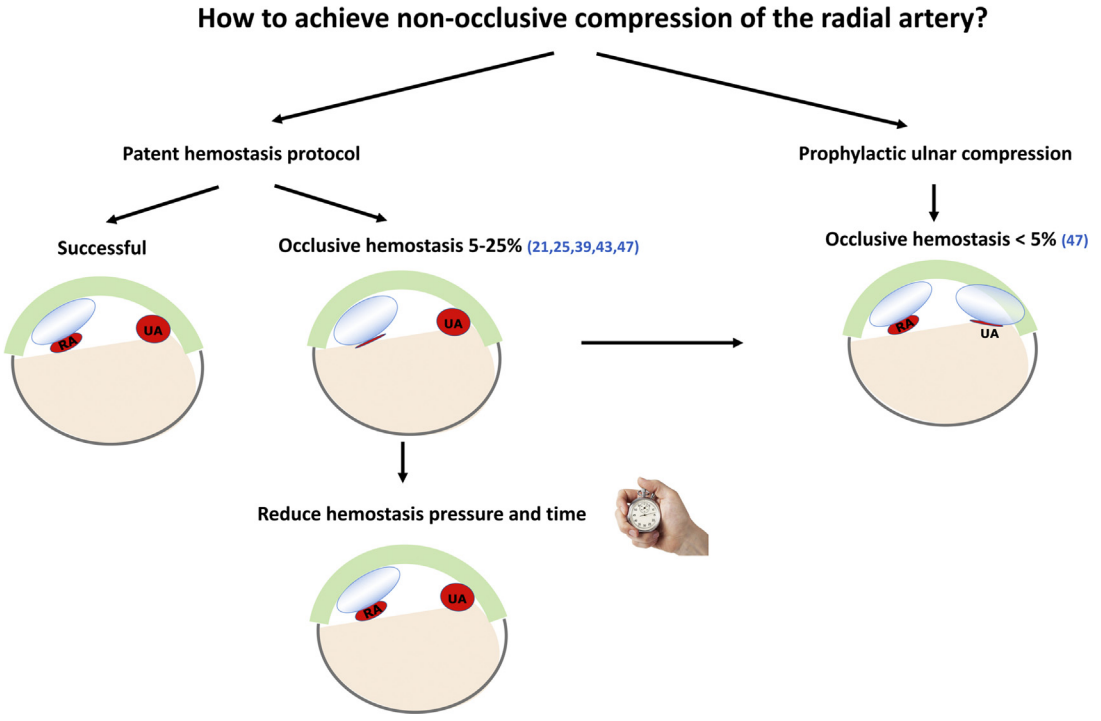
With the exception of thin-walled sheaths, the OD of standard sheaths is typically 2-F larger than the OD of the corresponding guiding catheter. Another strategy to minimize radial artery trauma is to perform sheathless TRA, which has been associated with low rates of RAO in relatively small-sized registries (2% to 5%) (35,36). In a single-center randomized study that included 600 patients undergoing TR percutaneous coronary intervention, use of a 6.5-F sheathless guiding catheter was associated with a lower combined rate of RAO and spasm than a 6-F thin-walled sheath (0.7% vs. 3.7%; p = 0.021), but crude rates of RAO were not significantly different (0% vs. 1.7%; p = 0.062) (37). Although the OD of these sheathless catheters are considerably lower than the OD of standard radial sheaths, only limited evidence exists regarding the true impact on RAO prevention. The use of pre-procedural ultrasound might also provide important information regarding the size of the radial artery, avoiding as such the insertion of sheaths and catheters larger than the vessel size.

To limit the sheath-to-artery mismatch, radial operators should preferentially select smaller sized sheaths and catheters or use thin-walled radial sheaths, whenever possible (**Figure 1**). The general recommendation is to favor the use of the lowest profile system necessary to complete the procedure.

IMPORTANCE OF ADEQUATE PROCEDURAL ANTICOAGULATION. As thrombus formation is a key parameter leading to early RAO, adequate procedural anticoagulation is an important method to prevent RAO. According to a recent international survey, the majority of participants (92.5%) use unfractionated heparin (UFH) for diagnostic transradial cardiac catheterization, with significant practice differences in dose and route of administration (38).

The impact of anticoagulation intensity was previously assessed in several meta-analyses (8,21,39). Overall, the rate of RAO was significantly reduced when using "high-dose" UFH (i.e., ≥5,000 IU or ≥75 IU/kg) versus "low-dose" UFH (<5,000 IU or up to 50 IU/kg body weight). Despite this relatively large body of evidence, there was still an ongoing debate on what should be considered as "adequate" anticoagulation during TR access. Recently, the multicenter SPIRIT OF ARTEMIS (Studying the Priority of Anticoagulation to Prevent Arterial Occlusion After Forearm Angiographies) study has randomized 1,836 patients undergoing TRA diagnostic coronary angiography to a high dose UFH (100 IU/kg body weight) or a standard dose UFH (50 IU/kg body weight). In the high-dose UFH group, the rate of RAO was significantly lower compared with the standard-dose group (3.0% vs. 8.1%; p < 0.001), without any significant increase for local hematomas or bleeding events (21). Among potential limitations of this trial, it should be noted that there was significant heterogeneity in RAO rates across recruiting centers (from 0.4% to 10%) and systematic "patent hemostasis" protocols were not used. The same authors have performed a pooled analysis of their integrated database and demonstrated that a UFH dose of >75 IU/kg compared with <50 IU/kg conferred a striking 80% risk reduction for RAO. By combining the results of SPIRIT OF ARTEMIS trial with the previous 5 randomized controlled trials in an updated meta-analysis, the authors found that more intensive compared with less intensive anticoagulation was associated with a significantly lower rate of RAO (3.6% vs. 9.4%; p = 0.02). Currently, UFH is the most extensively studied anticoagulant regimen for TR access, although other antithrombin agents such as enoxaparin or bivalirudin can also be considered. Of note, the protective effect of UFH on RAO has been shown to be similar whether it is administered through the arterial sheath or intravenously (40). In patients on oral anticoagulant therapy with warfarin and undergoing TRA procedure, UFH administration in a single-center observational study was associated with lower RAO rates (41). Further study is clearly required to define optimal intravenous anticoagulation regimen to reduce the risks of post-procedural RAO in patients with chronic oral anticoagulation. Altogether, there is now strong evidence to recommend a strategy of systematic intravascular anticoagulation with high-dose UFH to reduce the risk of RAO, although the

FIGURE 2 Flowchart to Achieve Nonocclusive Compression of the Radial Artery Following TRA Procedures



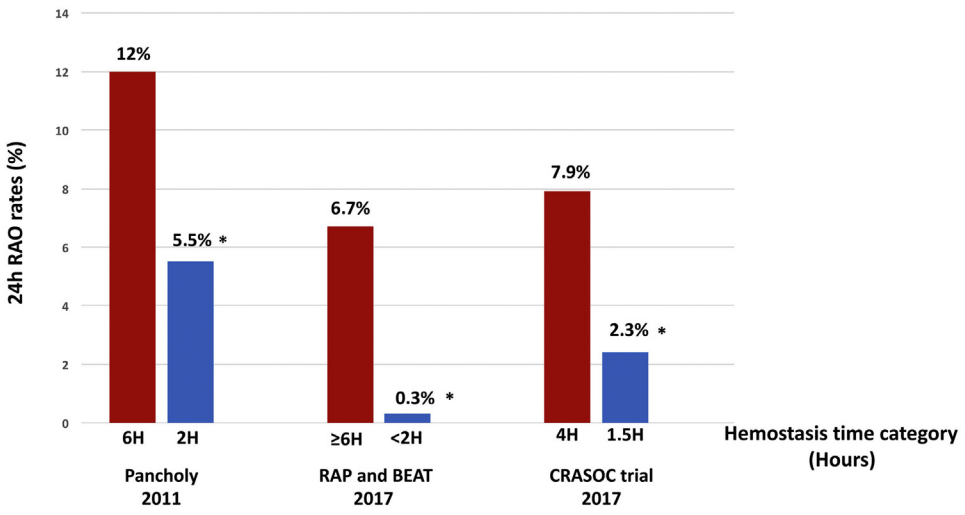
RA = radial artery; TRA = transradial access; UA = ulnar artery.

risk of major bleeding in this "high-dose" strategy remains to be determined in an adequately powered setting.

IMPORTANCE OF NONOCCLUSIVE OR "PATENT" HEMOSTASIS. During radial hemostasis, complete cessation of blood flow with "occlusive" compression promotes thrombus formation and is a strong predictor of RAO (23). Patent hemostasis is defined as the persistence of antegrade blood flow through the radial artery during hemostatic compression. In the landmark PROPHET (Prevention of Radial Artery Occlusion—Patent Hemostasis Evaluation Trial), 436 patients were randomized to undergo a patent hemostasis protocol (**Table 3**) or conventional pressure application for hemostasis after TR diagnostic coronary angiography. Patients assigned to the patent hemostasis protocol were associated with a significant decrease in early (<24 h) RAO rates from 12% to 5% and late RAO rates (30 days) from 7% to 1.8% (19). Similarly, in the randomized RACOMAP (Radial Compression Guided by Mean Artery Pressure Versus Standard Compression with a Pneumatic Device) trial, patent hemostasis was performed with a pneumatic compression device in which compression was guided by mean arterial pressure (maintaining thereby flow within the radial artery during hemostasis), demonstrating also a significant decrease in RAO rates from 12.0% to 1.1% (24). The concept of maintaining flow in the radial artery during hemostasis has since become a powerful nonpharmacological method for the prevention of RAO. Despite being simple and inexpensive, it requires significant involvement of the nursing staff due to the need for repeated oximetry-plethysmographic evaluation of radial flow and frequent adaptation of the hemostatic pressure to ensure ongoing vessel patency. As such, there is still limited adoption of the technique worldwide (9). Moreover, no attempt or failure to achieve patent hemostasis has been reported to occur in as high as 20% to 50% of patients (11,19,21,42). Therefore, several recent trials have explored potential alternative or device-based techniques to increase the adoption and success of nonocclusive hemostasis.

ADDITIONAL VALUE OF PROPHYLACTIC ULNAR COMPRESSION. The radial and ulnar arteries present an important hemodynamic interdependence because of extensive micro- and macro-collateralization of the forearm and palmar circulation (43).

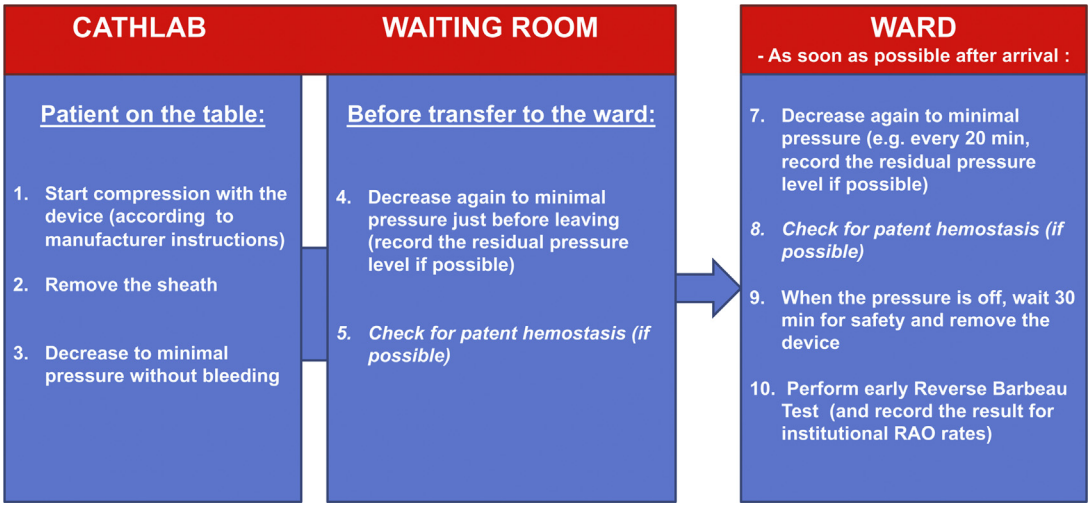
FIGURE 3 Impact of Shorter Hemostasis Times on RAO Rates



*p < 0.05 for all comparisons. CRASOC = Compression of Radial ArterieS without Occlusion; RAO = radial artery occlusion; RAP and BEAT = Radial Artery Patency and Bleeding, Efficacy, Adverse event.

Ipsilateral ulnar compression is associated with an increase in radial flow, thereby increasing the release of vasodilator mediators ("flow-mediated vasodilatation") (44). The PROPHET II (PROPhylactic Hyperperfusion Evaluation Trial) was a large randomized trial comparing prophylactic ulnar compression using a second compression device (while compressing the radial artery for hemostasis) against a standard patent hemostasis protocol after TRA for the prevention of RAO (42). As compared with patent hemostasis alone, the addition of prophylactic ipsilateral ulnar artery compression was associated with a significant reduction in the incidence of 24-h and 30-day RAO from 4.3% to 1.0% and 3.0% to 0.9%, respectively (p = 0.0001 for both comparisons). Interestingly, patent hemostasis was successfully achieved in as high as 96% of patients assigned to prophylactic ulnar compression. Moreover, occlusive compression of

FIGURE 4 Simple and Effective Hemostasis Protocol Using a Dedicated Compression Device



RAO = radial artery occlusion.

TABLE 4 Recommendations for the Detection and Prevention of RAO

	Level of Evidence	(Ref. #)
1. Importance of reducing sheath/catheter size		
The general recommendation is to favor the use of the lowest profile system necessary to complete the procedure.	Randomized trials/meta-analysis/ observational studies	(8,11,18,20)
In case of higher risk of RAO, operators might consider the use of thin-walled sheaths or sheathless techniques, whenever possible.	Randomized trials/observational studies	(34,35,37)
2. Importance of adequate procedural anticoagulation		
Based on the large amount of evidence, we recommend that anticoagulation with UFH or LMWH equivalent be administered for all TRA cases, even for diagnostic only. Based on recent evidence, we recommend the administration of ≥75 IU/kg UFH for all procedures. When using LMWH, a dose of 0.5 mg/kg should be considered.	Randomized trials/meta-analysis	(8,21,38,39,59)
Although not assessed in dedicated trials, we suggest a maximal dose of 10,000 IU UFH in case of diagnostic procedures in obese patients.	Consensus opinion	
3. Importance of achieving nonocclusive hemostasis		
A patent hemostasis protocol, with or without prophylactic ulnar compression is a strong preventive measure against RAO and should be attempted whenever possible.	Randomized trials/meta-analysis/ observational studies	(8,18,19,23,24,42)
4. Importance of applying a minimal pressure strategy together with short hemostasis time (≤120 min)		
A potential simple and effective hemostasis protocol, using a dedicated compression device is depicted in Figure 4.	Randomized trials/observational studies	(19,25,26,28,45)
5. Pre-puncture subcutaneous nitrates and post-procedural pre-hemostasis intra-arterial nitrates can be considered whenever possible*	Randomized trials	(27,31)
The subcutaneous injection of 0.5 ml 0.1% of nitroglycerin at the radial artery puncture site and intra-arterial injection of 500 μg of nitroglycerin through the sheath at the end of the radial procedure are 2 simple and potentially effective methods associated with a reduced rate of RAO		
6. Patients undergoing transradial procedures should have a systematic assessment of radial artery patency before discharge.	Consensus opinion	
The oximetry-plethysmography test is considered as the method of choice for the detection of RAO, due to its widespread availability, ease of use and limited cost. In case of suspicion of RAO, duplex US imaging remains the gold standard technique to confirm RAO.		
7. Every TRA program should have a quality control program to assess their post-procedural RAO rate before hospital discharge and aims for <5% as demonstrated in the most recent large randomized trials.	Consensus opinion	

*Requires further study/validation.

IU = international units; LMWH = low-molecular-weight heparin; RAO = radial artery occlusion; TRA = transradial access; UFH = unfractionated heparin; US = ultrasound.

ulnar artery did allow continuous monitoring of radial artery patency by using continuous oximetry-plethysmographic monitoring of the ipsilateral thumb with automated alarms, thereby eliminating the need for repeat evaluations. The current lack of widespread availability of a dedicated device allowing for dual radial-ulnar compression is one of the remaining limitations for the adoption of this simple and effective technique to prevent RAO.

IMPORTANCE OF DURATION AND MAGNITUDE OF COMPRESSION IN RELATION TO RAO. Another important method to prevent RAO is to shorten the duration of hemostatic compression, which can itself favor maintenance of patent hemostasis. Indeed, the impact of patent hemostasis and hemostasis time on RAO are closely linked and interdependent (Figure 2). For instance, in case of initial failure to perform patent hemostasis, a longer hemostasis time will further increase the risk of RAO by prolonging the duration of blood stasis. In a small nonrandomized study, Edris et al. (45) have shown the benefit of applying a simple rapid deflation technique using the TR-band device (minimal pressure applied 15 min after sheath removal, mean air volume 8.1 ± 2 ml), leading to a very high rate of patent hemostasis (95%) and a low rate of early RAO, as compared with a standard deflation technique (2% vs. 14.5%; $p < 0.005$) (45). In the series of CRASOC (Compression of Radial ArterieS without Occlusion) studies, which have included data from 3,616 patients randomized to 3 consecutive protocols, the rate of RAO was markedly reduced when hemostatic compression was mild and short (1.5 h), resulting in a 2.3% rate of RAO versus 9.4% when stronger pressure and longer (4 h) compression time were applied (26). The CRASOC trials highlight the effectiveness of combining a minimal pressure strategy with a short compression duration for the prevention RAO. Use of such strategies can significantly simplify the workload for the post-procedural care team, hence extending the adoption and successful application of nonocclusive hemostasis (44).

In the RAP and BEAT 2 × 2 factorial trial, patients were randomized to undergo a systematic patent-hemostasis protocol using the TR band or the standard institutional hemostasis protocol. Interestingly, this study found no additional benefit of using the standard patent hemostasis protocol over the

institutional protocol on the rate of RAO (2.6% vs. 2.6%; p = 0.99) (18). This apparent lack of benefit of applying standard patent hemostasis was likely related to the inclusion of experienced radial centers with established institutional hemostasis protocols, using already minimal pressure strategies and short hemostasis duration (selection bias), as evidenced by the overall low RAO rates. Of note, hemostasis time was shown to be an independent predictor of RAO (28). The adjunctive use of an "hemostatic" patch to the compression device can further shorten hemostasis time (46). Although radial hemostasis should be kept within a short time frame, ultrashort compression duration may be associated with an increased rate of puncture site rebleeding, which could paradoxically increase the rate of RAO, due to the requirement of reincreasing hemostatic pressure, which then leads to occlusive compression (26,47).

Overall, current evidence strongly suggests that shorter compression duration (≤120 min) is associated with reduced risk of RAO (**Figure 3**). A potential simple and effective hemostasis protocol, using a dedicated compression device is depicted in **Figure 4**.

TREATMENT OF RAO. In case of early RAO, a pharmacological approach with low-molecular-weight heparin or a nonpharmacological approach with transient ulnar artery compression can be considered. The use of low-molecular-weight heparin with therapy duration from 1 to 4 weeks resulted in successful radial artery reopening rate of 56% to 87% (48,49). In a randomized trial of 465 patients, early treatment of RAO with 1-h ulnar artery compression in a group with higher dose of heparin (5,000 IU) was associated with radial artery recanalization in 71% of patients with a final incidence of <1% RAO (50). Invasive recanalization of RAO using antegrade or retrograde techniques has also been reported, and can be considered in case of symptomatic hand ischemia or if there is a clinical need to reopen an occluded radial artery for TR procedure (51,52). For patients presenting with symptomatic post-procedural RAO, further evidence is required to assess the risks and benefits of prolonged therapy with anticoagulant agents or nonpharmacological therapy.

FUTURE PERSPECTIVES ON DISTAL RADIAL ACCESS

Recently, the distal radial artery from the anatomical snuffbox on the dorsal side of the hand ("distal TRA" or "snuffbox access") has emerged as an alternative access to the conventional forearm radial artery for coronary angiography and interventions. Beyond potential advantages related to improved operator comfort, easier and shorter hemostasis due to the more superficial position of the distal radial artery, distal TRA bears a physiological and anatomical sound rationale for reducing the rate of forearm RAO (53). Indeed, an important feature of this technique is a puncture distal to the superficial palmar arch. As such, distal TRA has the potential to maintain anterograde flow in the forearm radial artery during hemostatic compression or in case of distal radial artery occlusion, reducing thereby the risk of retrograde thrombus formation. The current available data on distal TRA is limited to observational case series looking primarily at the feasibility and success rates with this approach (54-56). Interestingly, most studies have reported <1% case of forearm RAO. A randomized comparison of distal TRA with conventional TRA for the prevention of forearm RAO is needed to assess the potential benefit and limitations of this alternative access.

RECOMMENDATIONS FOR THE DETECTION AND PREVENTION OF RAO

As described previously, prevention of RAO requires a multifactorial approach. It should take into account each of the components of the Virchow triad by minimizing vascular injury, avoiding a hypercoagulable state and blood stasis. Based on the current state of evidence, recommendations provided by the group are summarized in **Table 4**.

CONCLUSIONS

We have summarized the main recent advances in the field of RAO prevention. This consensus document is meant to provide guidance to radial operators to increase the adoption of efficient and simple preventive strategies to achieve an institutional rate of early RAO <5%. These recommendations reflect the most recent evidence but should be revised with continuing progress in the field.

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