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STATE-OF-THE-ART REVIEW

CORONARY

Coronary Artery Fistulas

Indications, Techniques, Outcomes, and Complications of Transcatheter Fistula Closure

Mohammed Al-Hijji, MD,[a,b] Abdallah El Sabbagh, MD,[c] Stephanie El Hajj, MD,[a] Mohamad AlKhouli, MD,[a] Bassim El Sabawi, MD,[a] Allison Cabalka, MD,[a] William R. Miranda, MD,[a] David R. Holmes, MD,[a] Charanjit S. Rihal, MD[a]

ABSTRACT

Coronary artery fistulas (CAFs) are rare coronary anomalies that are usually diagnosed incidentally with cardiac imaging. Small CAFs are generally asymptomatic and can close over time, while some untreated medium or large CAFs can enlarge, leading to clinical sequelae such as cardiac chamber enlargement or myocardial ischemia. With the advancement of transcatheter equipment and techniques, CAFs have been increasingly closed using a percutaneous approach. However, the procedure is not free of limitations given the risk for myocardial infarction, device embolization, and fistula recanalization. In this review, the authors illustrate the contemporary procedural considerations, techniques, and outcomes of transcatheter CAF closure. (J Am Coll Cardiol Intv 2021;14:1393–406) © 2021 by the American College of Cardiology Foundation.

Coronary artery fistulas (CAFs) are rare coronary anomalies, affecting 0.1% to 0.2% of the population (1–5). They are usually diagnosed incidentally during coronary angiography or noninvasive cardiac imaging. The majority of CAFs are congenital, but they are increasingly being seen following intracardiac device implantation, cardiac surgery, myocardial biopsy, or direct chest trauma. CAFs may develop between the coronary artery and an adjacent vein, cardiac chamber, or other mediastinal structures. In all cases, the abnormal vessel lacks an outlet capillary bed, leading to minimal resistance to flow. In sizable fistulas, this often leads to marked shunting and progressive dilatation of the fistula. Clinical sequelae of CAFs may include cardiac chamber dilatation and dyspnea, as well as symptoms of ischemia (6). Although most patients have a single CAF, 20% of patients have fistulas originating from 2 or more coronary arteries (5,7,8). CAFs can be classified as small, medium, or large if the fistula diameter is <1, ≥1 to 2, or >2 times the largest diameter of the coronary vessel not feeding the coronary fistula, respectively. Small CAFs likely close spontaneously over time (9,10), while larger CAFs may require surgical or transcatheter closure. There is no high-quality evidence beyond small case series to guide the management of CAFs. Our consensus approach, derived from clinical experience, uses both patient and procedural factors to define the indication and optimal method of closing CAFs. In this study we review our consensus approach for contemporary assessment and interventional management of CAFs, highlighting contemporary transcatheter fistula closure techniques.

From the [a]Department of Cardiovascular Medicine, Mayo Clinic, Rochester, Minnesota, USA; [b]Heart Hospital, Hamad Medical Corporation, Doha, Qatar; and the [c]Department of Cardiovascular Medicine, Mayo Clinic, Jacksonville, Florida, USA.
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ABBREVIATIONS AND ACRONYMS

AV = arteriovenous

AVP = Amplatzer Vascular Plug

CAF = coronary artery fistula

CT = computed tomographic

MI = myocardial infarction

RCA = right coronary artery

INDICATIONS FOR CLOSURE

Untreated CAFs can lead to myocardial ischemia (11,12), endarteritis (13,14), cardiac chamber enlargement, or ventricular dysfunction (15). However, data supporting their closure are limited to small case series. Hence, specific societal guidelines to guide their management are lacking. The updated 2018 American College of Cardiology/American Heart Association guidelines (16) emphasized the importance of a heart team approach to evaluate the appropriateness and feasibility of CAF closure at centers with expertise in both percutaneous and surgical closure techniques. In our experience, common clinical scenarios in which CAF closure may be considered are listed in **Table 1**. It is important to note that small CAFs usually close spontaneously over time (9,10), and therefore they can be monitored without intervention. Medium- or larger size fistulas can enlarge over time, especially in pediatric and young adult patients (17). These types of fistulas are usually associated with proximal coronary artery dilatation signifying high shunt flow over the years. In our practice, medium-size fistulas are closed early before further growth, as closure of larger fistulas is associated with higher risk for myocardial infarction (MI) (18–20). Our recommendation for the evaluation and management of CAFs, on the basis of careful analysis of the anticipated benefits and risks of the procedures, is shown in **Figure 1**.

Transcatheter closure of CAF was first performed by Reidy et al. (21) in 1983 using a detachable balloon technique. Since then, considerable advances have been made in interventional devices, such as the development of detachable coils and vascular occluders (4,6,8). The goal of closure is to interrupt flow in the body of the fistula. In our experience, there are few main types of fistulas encountered (18,22):

1. Fistulas that originate from the proximal left anterior descending coronary artery to the pulmonary artery (**Figure 2A**). These are typically weblike arteriovenous (AV) malformations. They are generally small incidental findings and do not need to be closed.
2. Fistulas that originate from left circumflex coronary artery to the coronary sinus (**Figure 2B**). These have the tendency to dilate and reach large sizes. They should be closed when diagnosed unless they are too large (≥10 mm), which can lead to stagnant flow after closure (23,24). Stagnant flow can increase the risk for MI, as discussed later.
3. Fistulas that originate from the middle or proximal right coronary artery (RCA) to a venous structure (**Figure 2C**). They similarly may enlarge if left untreated.

HIGHLIGHTS

- CAF can present with various anatomic configurations and clinical syndromes.
- Closure can be effective treatment for carefully selected symptomatic CAF.
- CAF closure procedures can be complicated by post-procedural MI.
- Large registries are needed to understand the natural history of various CAF.

4. Fistulas that originate from the distal RCA to the coronary sinus (**Figure 2D**). These are particularly challenging to close because the proximal RCA can dilate markedly, which increases the risk for MI after closure, as discussed later.
5. Acquired CAFs (**Figure 2E**). These are usually easier to close and are associated with high closure success rates (18,25).

DIAGNOSIS AND PROCEDURAL PLANNING

Although CAFs may cause symptoms, most are diagnosed incidentally during cardiac imaging. The results of physical examination are often normal. In rare cases, a continuous flow murmur is present. Other physical examination and imaging findings of cardiac chamber enlargement, volume overload, and atrioventricular valve incompetence can be present.

Pre-procedural echocardiography plays a critical role in assessing the hemodynamic significance of CAFs, excluding other associated anomalies, and monitoring response to therapy. Echocardiography is needed for baseline measurement of atrial and ventricular chamber dimensions, as well as screening for pulmonary hypertension and increased cardiac output. Moreover, echocardiography can help provide detailed anatomic understanding of the proximity of neighboring structures, such as atrioventricular valves, that can be impinged with certain CAF closure techniques.

Multidetector cardiac computed tomographic (CT) imaging can be helpful in pre-procedural planning, especially in patients with larger communications to the right atrium, coronary sinus, or right ventricle. Three-dimensional volume-rendered studies define the fistula origin and site of termination, fistula size, and anatomic course (Supplemental Figure 1). Furthermore, CT planning can aid in the selection of a surgical versus a percutaneous approach to treatment, selection of device size, prediction of

TABLE 1 Indications for CAF Closure

Symptomatic medium or large CAF*
1. Evidence of ischemia in the feeder artery territory
2. Arrhythmia thought to be related to CAF
3. Endarteritis
4. Vessel rupture
5. Cardiac chamber enlargement
6. Ventricular dysfunction

*A medium fistula is defined as a vessel diameter that is ≥1 to 2 times the largest diameter of the coronary vessel not feeding the coronary fistula. A large fistula is defined as a vessel diameter that is more than 2 times the largest diameter of the coronary vessel not feeding the coronary fistula.

CAF = coronary artery fistula.

embolization destinations, and identifying optimal working fluoroscopic angles.

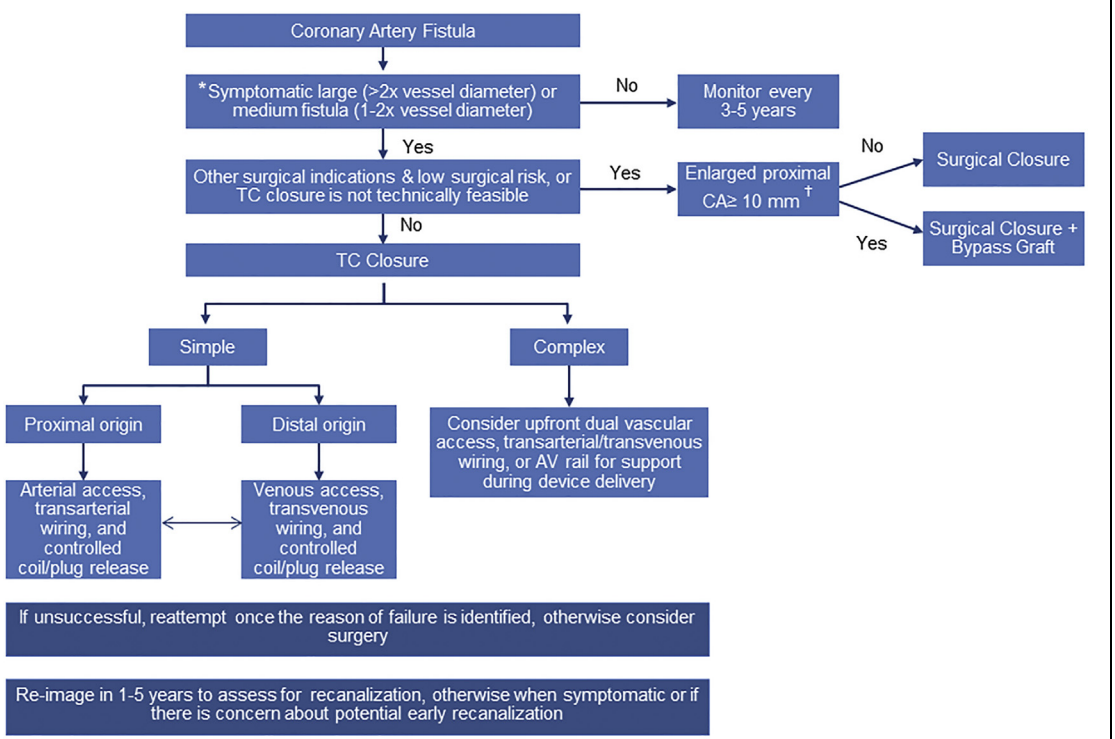
Pre-procedural coronary angiography is useful to delineate the fistula anatomy in fluoroscopic projections that can be replicated during transcatheter closure. However, visualization of the parent vessel is often challenging because of overlap from a tortuous fistula. Additionally, high-volume flow can make it difficult to fully opacify the fistula with contrast. Opacification may be improved using larger diameter catheters, automated contrast power injection (Supplemental Figure 2), balloon occlusion of the distal fistula, or simultaneous dual injection of the fistula's origin and termination.

TECHNIQUE OF CLOSURE: ANATOMIC CONSIDERATIONS

See the **Central Illustration** for an algorithm for CAF closure for fistulas originating from the proximal coronary bed and the distal coronary bed.

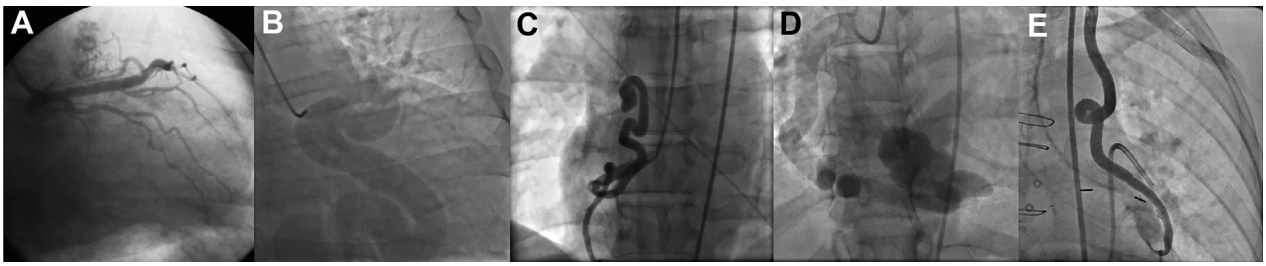
CAF ORIGINATING FROM PROXIMAL CORONARY SEGMENTS. The approach to closure of a CAF originating from proximal coronary artery segments starts with evaluating the origin(s) of the fistula. In most

FIGURE 1 Algorithm of Coronary Artery Fistula Evaluation and Management



*Symptomatic fistulas are coronary artery (CA) fistulas that potentially lead to myocardial ischemia, vessel aneurysm and rupture, endocarditis, unexplained cardiac chamber enlargement/dysfunction, or arrhythmia. †An enlarged proximal CA with diameter ≥10 mm has a tendency to thrombose after fistula closure, resulting in myocardial infarction. A simple fistula has a single-vessel origin, simply defined pathways, and a clearly defined termination. A complex fistula is a large fistula with multiple origins and plexiform formation.
AV = arteriovenous; TC = transcatheter.

FIGURE 2 Main Types of Coronary Artery Fistulas



(A) Small fistula from left anterior descending coronary artery to pulmonary artery (PA) with weblike communications. **(B)** Large fistula originating from the distal left circumflex coronary artery and terminating into the coronary sinus (CS). **(C)** Moderate-size fistula originating from the right coronary artery (RCA) and emptying into the superior vena cava–right atrium junction. **(D)** Large fistula originating from the RCA and terminating into the CS. **(E)** Fistula from left internal mammary (LIMA) to left PA. LIMA angiography showed a distal segment emptying into the left PA. Also, the PA catheter was positioned in the left PA.

patients, several feeders, coronary artery branches that provide fistulous connections to venous structures, exist, and it is important to find the angiographic projections that delineate their origins. Successful closure requires eliminating flow of the fistula confluence or all feeders. In rare situations, the origins can be ambiguous or consist of multiple hairlike fistulas (plexiform fistulas), which cannot be crossed or closed from the arterial or venous sides. A last resort in that circumstance would be to proceed with deployment of a stent graft (covered stent) across CAF origins in the coronary artery after weighing the risk for stent thrombosis with stent grafts. If the fistula pathway is severely tortuous, coiling is favored because of the lower profile of the microcatheters and coils, making them easier to deliver. However, if the fistula size is sufficient and the course is straight, a vascular occluder device can be used.

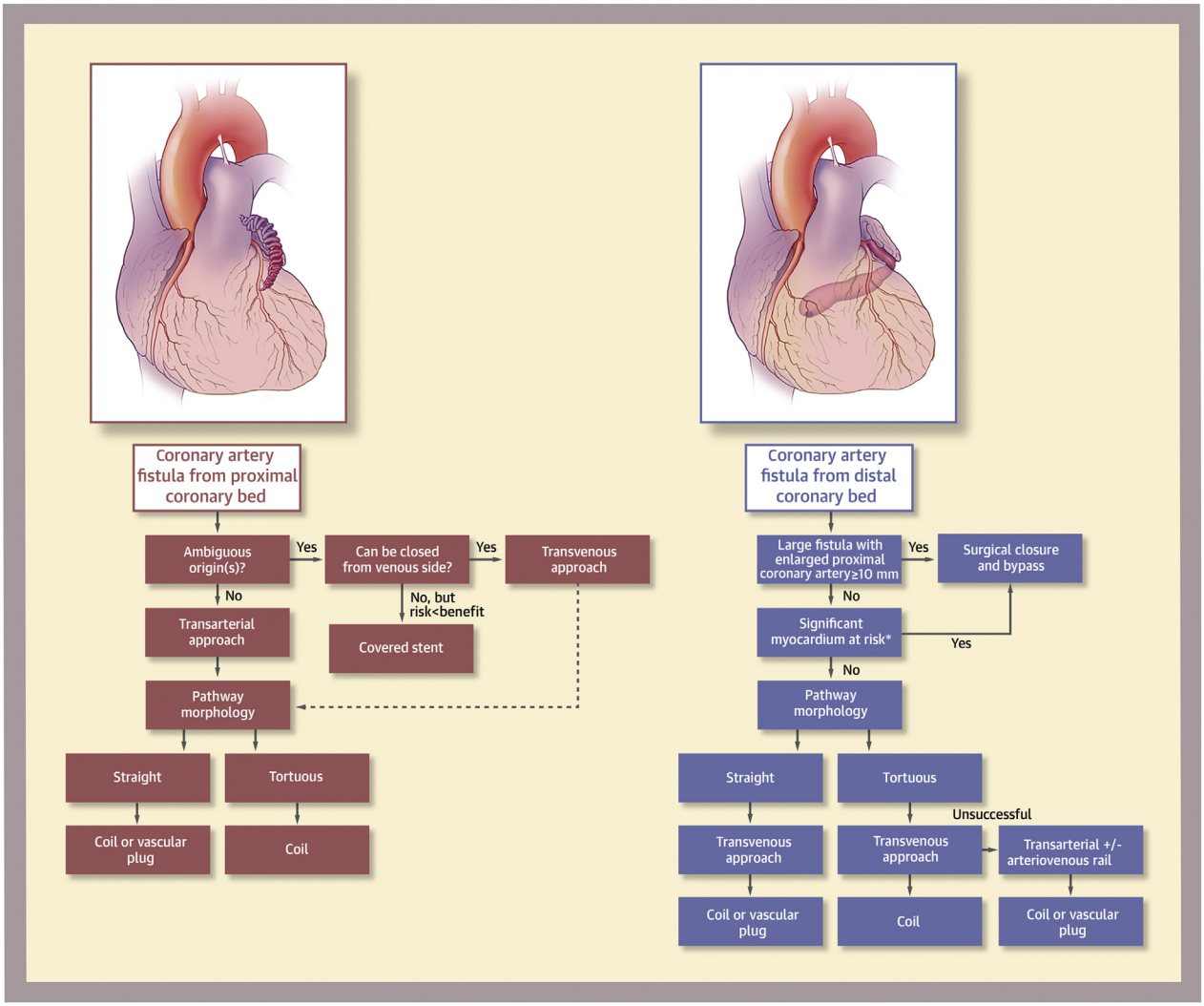
CAF ORIGINATING FROM DISTAL CORONARY SEGMENTS. Closure of a CAF originating from the distal coronary segments takes into consideration the size of the fistula, along with the size and number of coronary artery branches that come off the aneurysmal section of the native coronary artery before it continues as the fistula distally (myocardium at risk). The Achilles' heel of closure of a CAF originating from distal coronary segments is MI (18,22). This can result from large thrombus formation in the proximal aneurysmal part of the feeding coronary artery secondary to the development of stagnant flow after CAF closure (23,24). MI can also result from small layered thrombus embolization from the proximal aneurysmal vessel to the distal side branches or inadvertent closure of these vessels with the transcatheter closure device. If the coronary aneurysm is markedly enlarged or the myocardium at risk is significant, surgical closure and surgical bypass of the distal branches to preserve coronary flow may be favored. If a percutaneous approach is feasible, closure technique depends on the length and tortuosity of the fistula pathway. The goal of closure in this setting is to disrupt flow distal to the coronary artery side branches to avoid closure device prolapse into these branch vessels.

TECHNIQUE OF CLOSURE: ACCESSING THE FISTULA

Figure 3 depicts transcatheter closure techniques, including the transarterial, transvenous, and AV loop approaches.

TRANSARTERIAL APPROACH. The transarterial approach is achieved by intubating and closing the fistula from the feeder (arterial) side, while the transvenous approach is performed by closing the fistula from the outlet (venous) side. The transarterial approach requires radial or femoral arterial access so that the fistula is accessed via the parent coronary vessel. The transarterial approach is most used for fistulas originating from the proximal coronary, as there is a shorter distance to traverse through the parent vessel (Figures 4A to 4C). To ensure adequate support, a 7- or 8-F guiding catheter is preferred. After the guiding catheter is engaged, the fistula is traversed with either a 0.014-inch coronary wire (small fistula) or a 0.035-inch hydrophilic wire (large fistula). For a small fistula, a soft-tipped workhorse 0.014-inch coronary guidewire is preferred to reduce the risk for vascular injury; however, occasionally

CENTRAL ILLUSTRATION **Algorithm of Coronary Artery Fistula Closure for Fistulas Originating From Proximal Coronary Bed and Distal Coronary Bed**



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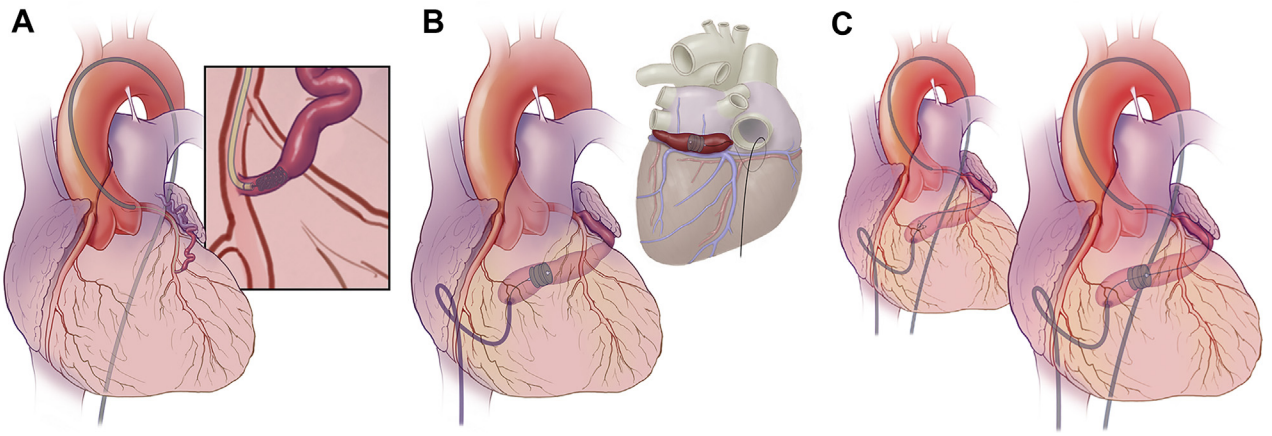
*Significant myocardium at risk is defined by the number and sizes of branches that might be compromised with closure of coronary artery fistula.

hydrophilic wires can be used to navigate extremely tortuous fistulas. Once the fistula has been traversed, a microcatheter or guide extension can be advanced over the 0.014-inch wire, or a guiding catheter can be deeply seated over a 0.035-inch wire using a telescoping catheter technique. Microcatheters are used when the CAF is small enough to permit embolization with pushable or detachable coils. In general, microcatheters with at least 0.018-inch inner diameter are required for coil delivery. The first coil deployed should be at least 30% oversized to the vessel diameter. If a gap remains on subsequent angiography, additional coils can be used to fully seal the fistula. Telescoping systems with larger catheters are required for vascular occluder device delivery (**Figures 4D to 4I**). The size of the delivery catheter depends on the occluder type and dimensions needed to close the fistula. We recommend that the occluder size be 50% larger than the diameter of the CAF. Operators should place the device ≥1 cm away from the origin of the fistula to reduce the risk for device prolapse and thrombus propagation. It is important to

FIGURE 3 Transcatheter Closure Techniques



(A) Transarterial approach. The coronary vessel is intubated, and the fistula is wired from its origin. The delivery catheter can then be delivered to the fistula over a wire for device deployment. The occlusion device is then deployed and released. **(B)** Transvenous approach. The fistula termination site is intubated with the delivery catheter. The delivery catheter is advanced over a wire to the appropriate landing zone. The occlusion device is then deployed and released. **(C)** Arteriovenous (AV) loop approach. In large and tortuous fistulas, AV rail can be formed with the aid of a snare device to maximize support for catheter and device delivery.

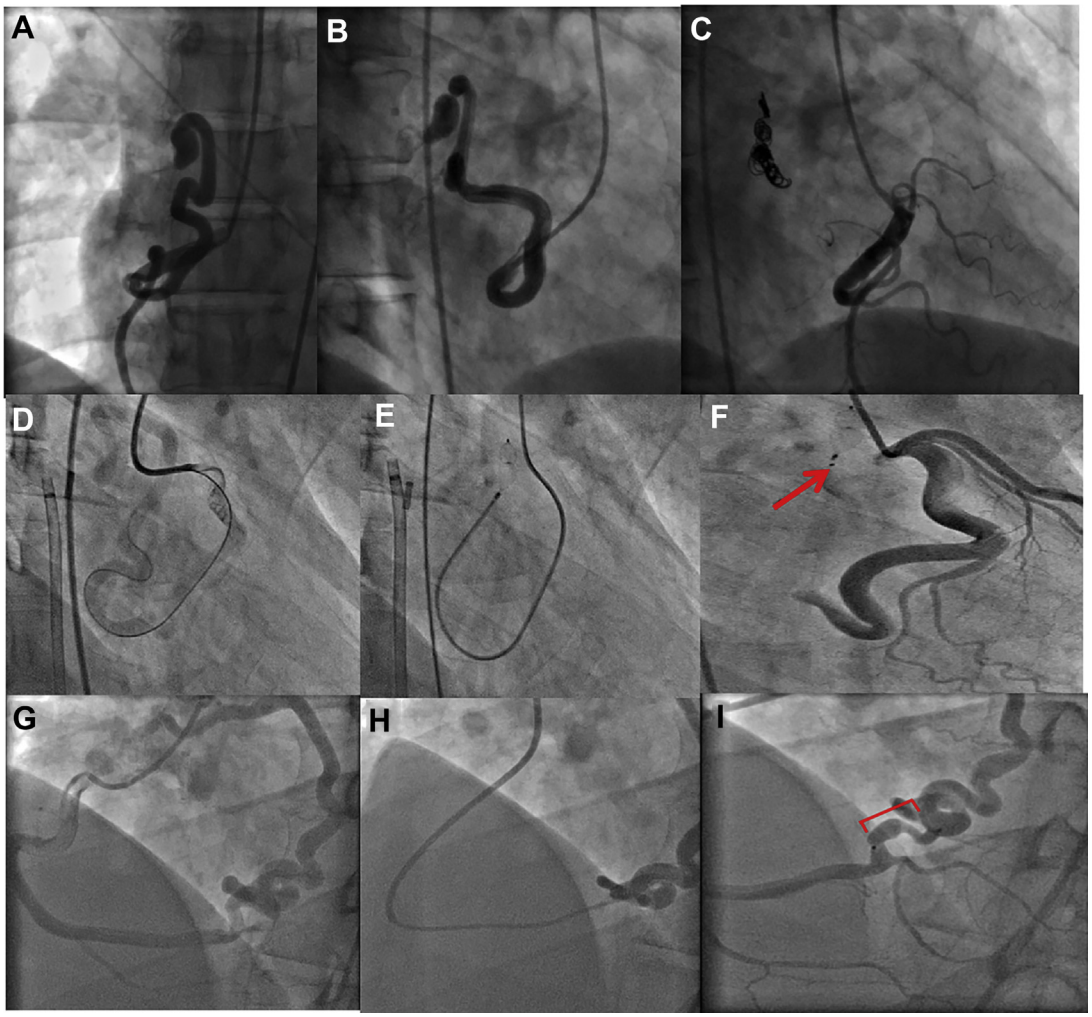
target and close the actual fistulous connection completely to reduce the risk for recanalization, as discussed later.

TRANSVENOUS APPROACH. Figures 5A to 5C depict an example of the transvenous approach. Femoral or internal jugular venous access is required for transvenous CAF closure, which allows access to the fistula from the site of its termination. When the fistula originates from the distal third of the coronary vessel, the transvenous approach is preferred, as it lowers the risk for traumatic disruption of the parent vessel.

Engaging the termination of the CAF can be challenging. CT planning can be important to find fluoroscopic angles and landmarks to guide successful engagement from the venous side. Depending on the location of the termination, different catheters, including pre-shaped coronary guiding catheters and deflectable sheaths such as the Agilis sheath (Abbott Vascular, Santa Clara, California) or the Dexterity sheath (Spirus Medical, Bridgewater, Massachusetts) can be used to direct wire crossing. Larger CAFs will require the deployment of vascular occluders through ≥5-F catheters. This can be accomplished by deep-seating a guide catheter or exchanging for a hydrophilic-coated braided sheath such as a Flexor shuttle sheath (Cook Medical, Bloomington, Indiana). This technique usually requires an extra-support angled hydrophilic 0.035-inch wire (Glidewire, Terumo Medical, Somerset, New Jersey). To minimize trauma from deep guide insertion, a telescoping catheter technique is used whereby a 100-cm, 6- to 7-F guiding catheter is advanced into the vessel over a 125-cm, 5-F multipurpose diagnostic catheter that acts as a dilator or an introducer. Once the hydrophilic-coated braided sheath or coronary guiding catheter is seated within the CAF, a vascular occluder with appropriate size and fit for the selected catheter can be extruded. Depending on the size of device deployed, the 0.035-inch wire can be left in place as an anchor wire to enhance support or facilitate sequential delivery of multiple devices (26). For example, a 7-F guide will permit a 12-mm Amplatzer Vascular Plug (AVP) II (Abbott Structural Heart, St. Paul, Minnesota) to be delivered when an anchor wire is used. For both coils and vascular occluders, the device should be deployed at least 1 cm from the ostium to reduce the risk for device embolization or thrombus propagation.

AV LOOP. In extremely tortuous or large distal fistulas, additional support may be required to facilitate wire crossing and delivery of equipment. In such cases, an AV rail can assist catheter and device delivery (Figures 6A to 6I). As described earlier, the fistula can be accessed either from the arterial or venous side. The wire is then snared and exteriorized, forming a continuous loop (AV rail) that can provide extra

FIGURE 4 Examples of the Transarterial Approach



(A to C) A 53-year-old patient with a recent history of acute coronary syndrome. **(A)** coronary angiography demonstrated a proximal right coronary artery (RCA)–to-superior vena cava (SVC) fistula with a single origin and a tortuous pathway. **(B)** Selective intubation of the fistula with a multipurpose (MP) guiding catheter was performed. **(C)** After guidewire crossing and microcatheter positioning, two 4-mm/2-mm Tornado coils and three 14 × 6 mm Nester coils were released, with excellent results. **(D to F)** A 45-year-old woman with supraventricular tachycardia and a large distal fistula from the left circumflex coronary artery (LCx) to the SVC–right atrium junction. **(D)** The LCx was successfully wired using an 0.035-inch extrastiff angled Glidewire after failing to wire the fistula from the venous side. **(E)** A 5-F, 125-cm MP diagnostic catheter was delivered deep into the fistula and an 8-mm Amplatzer Vascular Plug (AVP) IV was deployed. **(F)** Coronary angiography 5 min after protamine administration to enhance clotting of the AVP-IV device **(red arrow)** illustrated absence of flow into the fistula. **(G to I)** A 33-year-old man with a recent non-ST-segment elevation myocardial infarction in the setting of a large distal RCA fistula to the SVC. **(G)** Coronary angiography with a 7-F Judkins right guiding catheter demonstrated a large RCA with distal tortuous fistula emptying into the SVC. **(H)** The coaxial 90-cm Judkins right 4 guiding catheter and a 5-F, 125-cm MP catheter were successfully advanced to intubate the fistula over a 0.035-inch angled Glidewire. **(I)** An 8-mm AVP-IV device was successfully deployed in the proximal portion of the fistula away from the distal RCA branches.

support for catheter and device delivery from the venous or arterial side. This technique can be also used in distal fistulas that cannot be intubated from the venous side. In such cases, the initial wire crossing is from the arterial side, but the catheter is delivered from the venous side to minimize trauma to the fistula. A list of commonly used equipment for fistula closure is summarized in Table 2.

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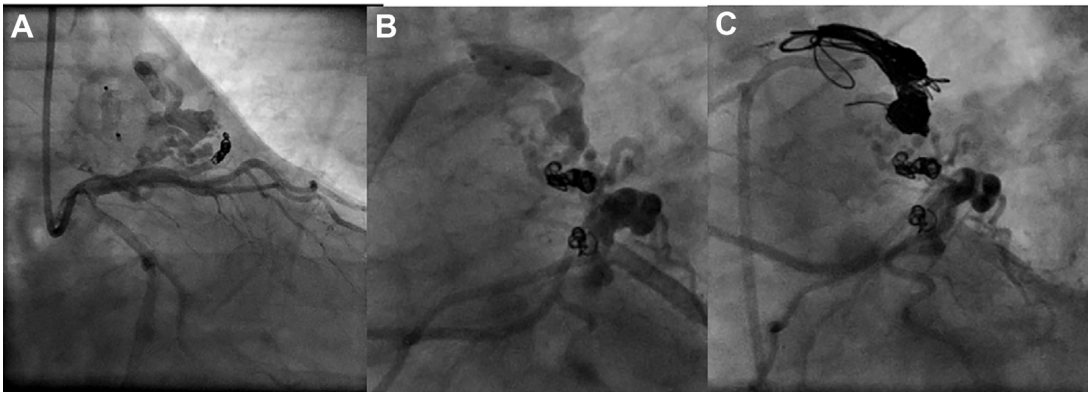
FIGURE 5 Example of Transvenous Approach



(A to C) A 65-year-old patient with a history of successful closure of a simple fistula from the proximal RCA into the PA with an AVP-II device and unsuccessful closure of complex fistula from the left anterior descending coronary artery (LAD) to the PA with pushable coils. **(A)** Coronary angiography revealed a complex fistula with multiple origins and pathways arising from the LAD and single termination into the main PA. **(B)** The mouth of the fistula was successfully intubated through the venous access site with a 7-F Amplatz left guiding catheter. **(C)** Three detachable EV3 20 × 50 cm coils were successfully released, abolishing the flow from the fistula into the PA. Abbreviations as in Figures 2 and 4.

DEVICE CHOICE

See Table 3 for a description of compatibility, advantages, and disadvantages of commonly used CAF closure devices.

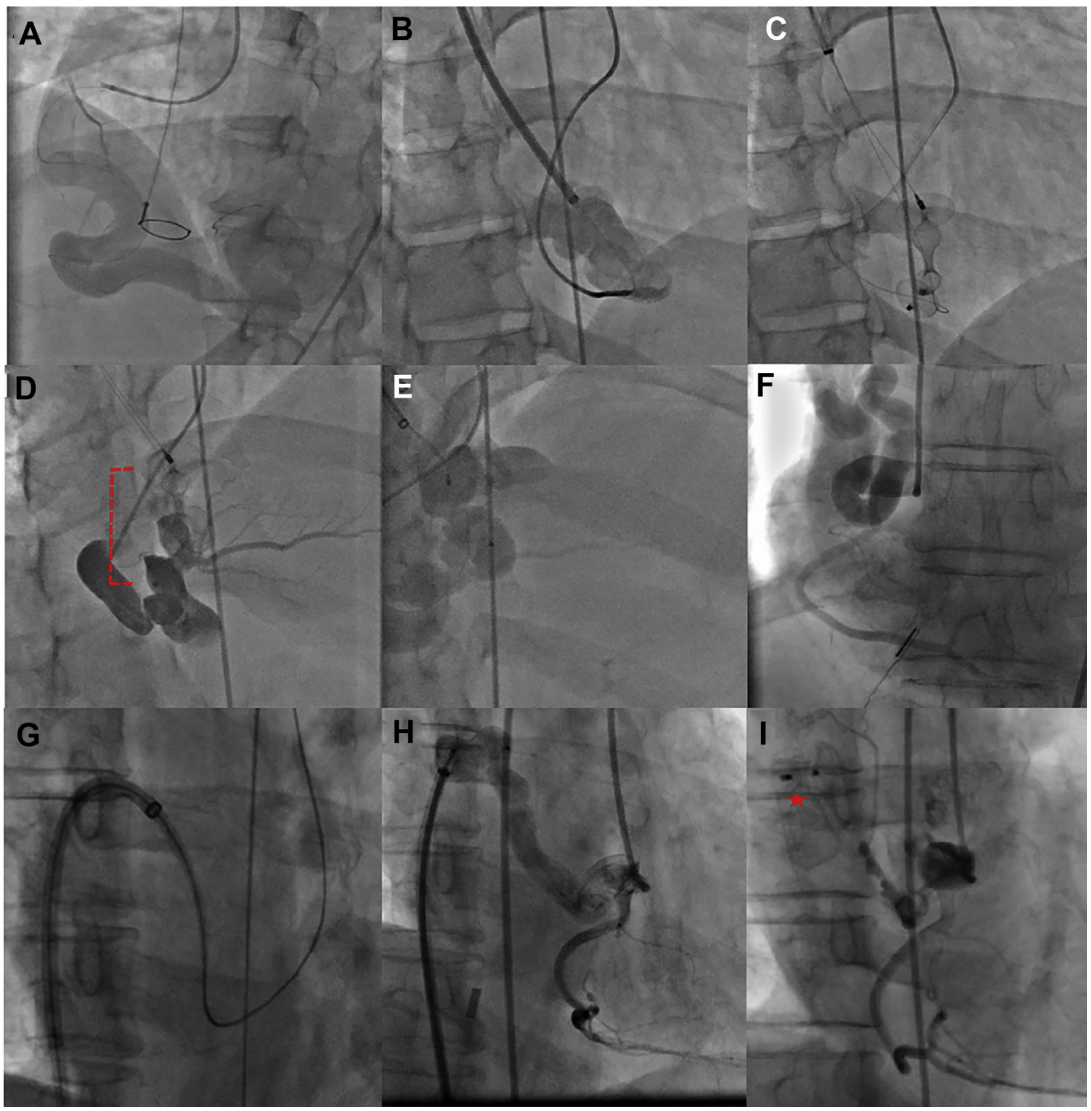
EMBOLIZATION COILS. Stainless steel or platinum coils are commonly used in transcatheter closure of CAFs, as they will conform to the vessel shape. Helical coils are widely used and can be stacked around a bend to anchor. An oversized 3-dimensional coil can also be deployed and serve as a backwall to allow stacking of helical coils behind it (block-and-bunch technique). The most commonly used coils are coated in fibers to increase thrombogenicity. Nester embolization coils (Cook Medical) are fibered pushable platinum coils that come in different diameters ranging from 2 to 20 mm. Tornado coils (Cook Medical) are another frequently used pushable fibered platinum coils. The Tornado coil has a tapered distal end intended to maximize packing of distal vessels. Both the Tornado and Nester coils are delivered through 0.018- to 0.035-inch microcatheters, depending on the required coil size.

Detachable coil systems such as the Azur platinum coil with expandable hydrogel polymer (Terumo Medical), fibered platinum coil Retracta (Cook Medical), and platinum coil Ruby (Penumbra, Alameda, California) are more expensive but are the coils of choice for larger fistulas in which the risk for device migration and/or embolization is higher. The coils are attached to a cable before final release. The coils are delivered through a low-profile 2.4- to 2.9-F, 100- to 150-cm microcatheter such as the Progreat coaxial microcatheter (Terumo Medical), Cantata microcatheter (Cook Medical), or Lantern microcatheter (Penumbra).

VASCULAR OCCLUDERS. AVPs are the most used occluders for CAFs in clinical practice. The Amplatzer devices are made of braided Nitinol mesh with interlocking struts. The device is attached to a 155-cm stainless steel cable that allows device repositioning before final release. The device accelerates fibrin-mediated thrombogenesis by minimizing flow through the Nitinol mesh.

There are 4 different iterations of AVP devices. The AVP-I has a single lobe with a cylindrical shape and can be used in fistulas with short landing zones. However, the single-lobe design permits more flow through the device, making it less thrombogenic, and therefore it is less commonly used. The AVP-II is the most used occluder at our institution. It is composed of 3 equally sized circular lobes made of densely braided Nitinol, which minimizes flow through the device and increases thrombogenicity. Additionally, the lobes are flexible, allowing the device to configure to the vessel, and the lobes can be overlapped such that multiple

FIGURE 6 Examples of Fistula Closure With the Aid of an AV Loop



(A to E) A 45-year-old patient with a large tortuous distal RCA communicating with the proximal CS. **(A)** Transarterial wiring was successful, with a 0.014-inch Whisper guidewire after failure to advance a 0.035-inch angled Glidewire through the tortuosity. A 5-F MP catheter and microcatheter were deeply intubated to provide support to advance coronary wire through the fistula termination. The wire was snared in the right atrium and exteriorized from the right internal jugular (RIJ) vein access with a Goose Neck snare. The microcatheter was advanced through RIJ sheath (kissing catheter and sheath), and the Whisper wire was switched for a supportive long-exchange 0.014-inch guidewire. **(B)** The microcatheter was removed and a 7-F shuttle sheath was delivered through the venous access past the fistula termination. **(C)** An 18-mm AVP-II device was successfully deployed. **(D)** Coronary angiography before release revealed that the device spanned the distal RCA branches. The device was retrieved and a smaller (14-mm) AVP-II device was deployed. **(E)** Coronary angiography revealed that the distal RCA branches were not at jeopardy with the 14-mm AVP II device. The device was successfully released afterward. **(F to I)** A 67-year-old woman with a history of endocarditis and proximal RCA-to-SVC fistula. **(F)** Coronary angiography demonstrated a tortuous fistula arising from the proximal RCA and emptying into the SVC. The distal RCA segment was normal in size. **(G)** Wiring the fistula through the SVC was difficult. Therefore, transarterial wiring was performed with an exchange-length angled 0.035-inch Glidewire that was exteriorized with the aid of a 4-F, 10-mm Goose Neck catheter. Over the created AV rail, an 8-F Cook Flexor sheath was delivered across the termination point of the fistula. **(H)** Coronary angiography helped visualize the position of an 8/10 Amplatzer Duct Occluder (ADO-I). **(I)** Coronary angiography after 5 min of partial reversal with protamine showed no residual flow across the released ADO-I device **(red star)**. Abbreviations as in Figures 1, 2, and 4.

TABLE 2 Equipment List Used for Device Delivery

100-cm guiding catheters
Microcatheter
Guide extension catheter
125-cm, 5-F multipurpose diagnostic catheter (for telescoping technique)
Hydrophilic-coated braided sheath, such as Flexor shuttle sheath (Cook Medical) or Destination sheath (Terumo Medical)
Deflectable sheaths, such as small- and medium-curl Agilis sheaths (Abbott Vascular) or Dexterity sheath (Spirus Medical)
0.014-inch coronary wire
0.035-inch hydrophilic Glidewire (regular and exchange length)
6-F Goose Neck (Medtronic) or En-Snare retrieval catheters (Merit Medical)

devices can be deployed. The AVP-III is similar to the AVP-II in that it is composed of 3 densely braided Nitinol lobes; however, it is oblong rather than round. The AVP-III is not available for use in the United States. The AVP-I, AVP-II, and AVP-III are delivered through 4- to 8-F catheters. The AVP-II provides the widest range of sizes, from 3 to 22 mm. The AVP-IV consists of 2 conical lobes with a relatively less dense Nitinol braid. The shape and composition of the AVP-IV allow easy deliverability through tortuous segments and make the AVP-IV compatible with a 0.038-inch inner diameter catheter; as a result the AVP-IV is well suited for complex fistulas. The use of ventricular septal defect and ductal occluder devices has also been described (27), but the AVP devices are preferred because they achieve complete occlusion and have a lower risk for hemolysis (28).

STENT GRAFTS. Deploying a stent graft in the parent coronary artery can be used to exclude plexiform fistulas with multiple origins or for lesions for which embolization with coils or occluders is not anatomically feasible. Stent grafts require consideration of oral anticoagulation or prolonged courses of dual-antiplatelet therapy because of the risk for stent thrombosis and MI. Careful consideration is required to be certain that significant-size arterial side branches will not be also occluded. In general, stent grafts are associated with 10% to 15% thrombosis risk, and therefore their routine use in CAFs is limited (29,30). The most commonly used stent graft, the JOSTENT GraftMaster (Abbott Vascular), is composed of a layer of polytetrafluoroethylene sandwiched between 2 stainless steel frames. The recently U.S. Food and Drug Administration-approved PK Papyrus stent (Biotronik, Lake Oswego, Oregon) consists of a single cobalt-chromium stent covered with a polyethylene membrane, making it more flexible and deliverable than the JOSTENT. Stent grafts are available in 2.5- to 5-mm diameters.

PROCEDURAL COMPLICATIONS

As in all coronary procedures, the risk for vessel trauma or dissection, rupture, and coronary pseudostenosis during wire and catheter delivery exists. Moreover, particularly for larger fistulas, there is a risk for device embolization, and it is prudent to study the pre-procedural CT scan to predict where the device would embolize to if the complication occurs. When embolization occurs, retrieval almost always can be achieved percutaneously with the use snare devices such as En-Snare (Merit Medical, South Jordan, Utah) and Goose Neck snare (Medtronic, Minneapolis, Minnesota). Equipment thrombosis is also a concern, and full intravenous heparin administration with goal activated clotting time of 250 to 300 ms is recommended to reduce the risk. Partial reversal with protamine is given at the end of the case to enhance clotting of the released device before final angiography.

MYOCARDIAL INFARCTION

MI can occur because of thrombus formation within the aneurysmal parent coronary artery, device thrombosis, or as a procedural complication (**Figure 7**).

The aneurysmal proximal coronary artery segments that develop in large distal CAFs are at risk for thrombus formation secondary to stagnant flow (31,32) after successful fistula closure. To reduce the risk for aneurysm thrombosis, our practice is to refer patients for surgical closure with concomitant surgical bypass and to initiate all patients with this anatomy on an indefinite course of long-term oral anticoagulation after successful closure. This approach in theory can preserve flow to the distal segment of the coronary vessel. However, surgical closure is also not free of risk for MI after closure of large fistulas. Five of 46 patients (11%) treated at the Mayo Clinic experienced post-operative infarction (22). In a series examining 76 patients who were medically managed or treated with surgery or transcatheter closure, infarction occurred in 15% (20). In the same series, the investigators found that drainage into the coronary sinus was a predictor of long-term ischemic events, as most of these fistulas originate from distal segments of ectatic coronary vessels. Closure of these types of fistula may be better performed when their size is moderate, before they grow further. Caution is needed with closure of a large distal fistula in the presence of an ectatic coronary vessel (≥10 mm in diameter), as these patients have elevated risk for perioperative MI.

TABLE 3 Compatibility, Advantages, and Disadvantages of Commonly Used CAF Closure Devices

Type of Device	Examples	Compatibility	Advantages	Disadvantages
Vascular plugs	AVP-II and AVP-IV	Guide or shuttle sheath	Good for large CAFs Repositionable Accelerated thrombogenicity	Large delivery catheter profile Need for additional support to deliver
Pushable coils	Nester coils (Cook Medical)	0.018- to 0.035-inch microcatheter, depending on required coil size	Easier to deliver Good for small, tortuous vessels Accelerated thrombogenicity	Embolization risk with pushable coils, lower risk with detachable coils given controlled release Inability to reposition with pushable coils Multiple coils needed to provide full seal of the flow
	Tornado coils (Cook Medical)	0.018- to 0.035-inch microcatheter, depending on required coil size		
Detachable coils	Retracta (Cook Medical)	0.035-inch internal diameter, 2.5- to 2.9-F, 100- to 150-cm microcatheter such as the Cantata microcatheter (Cook Medical)		
	Ruby (Penumbra)	0.025-inch internal diameter Lantern microcatheter (Penumbra)		
	Azur (Terumo Medical)	0.018- to 0.035-inch internal diameter Progret microcatheter (Terumo Medical)		
	Concerto (Medtronic)	0.017- to 0.021-inch internal diameter		
Stent grafts	JOSTENT GraftMaster (Abbott Vascular)	6-F guide for 2.8–4.0 mm 7-F guide for 4.5–4.8 mm	Treat plexiform fistula	High thrombosis risk
	PK Papyrus stent (Biotronik)	5-F guide for 2.5–4.0 mm 6-F guide for 4.5–5.0 mm		

AVP = Amplatzer Vascular Plug; CAF = coronary artery fistula.

MI can also occur because of occlusion of the distal segment or a side branch. Precise placement of the closure device >1 cm away from the origin of the fistula can reduce the risk for device thrombus propagation or embolization back into the coronary artery.

OUTCOMES OF CAF CLOSURE

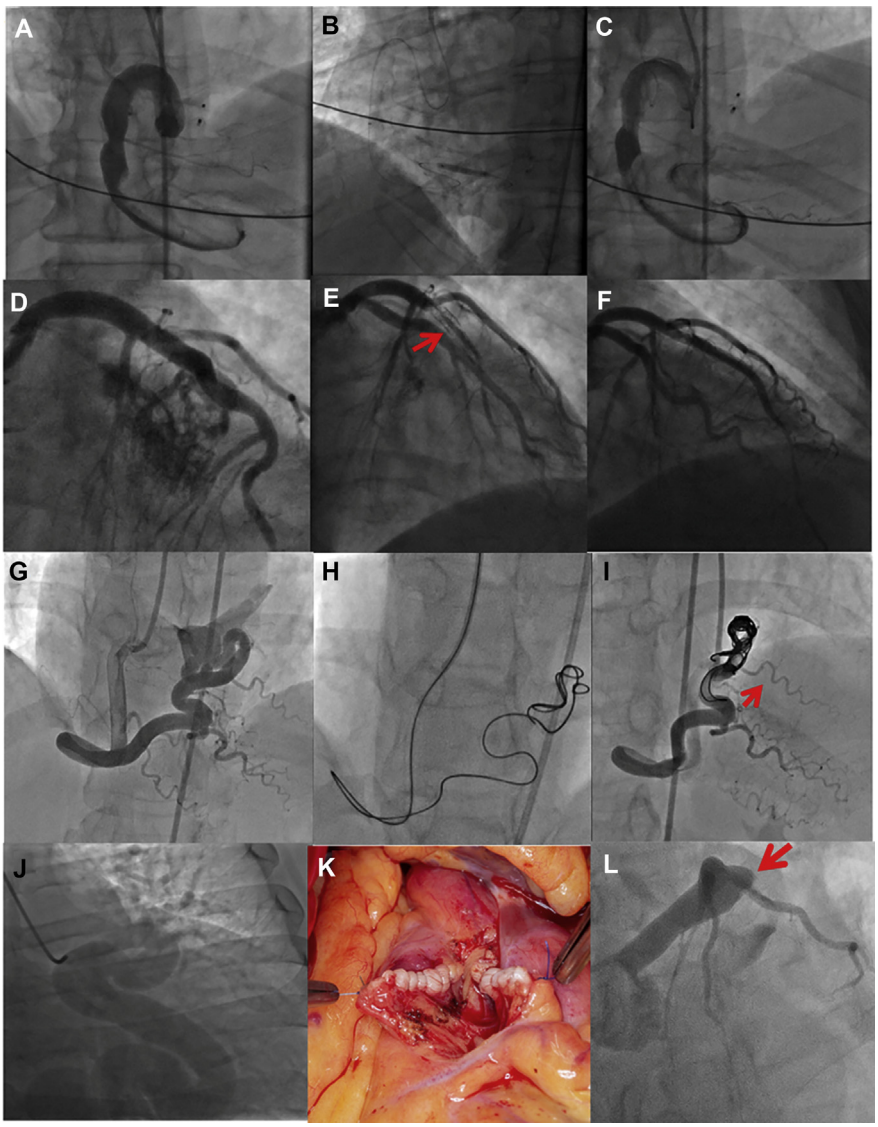
Reported outcomes from limited case series on transcatheter CAF closure demonstrate that this procedure is effective in most patients with suitable anatomy; however, it is not free of risks. A recent analysis from our center showed a 90% acute procedural success rate in 45 patients with 56 CAF closures. Complications included device migration in 3 patients, intracranial hemorrhage in 1 patient, and MI in 4 patients (18). All device embolization cases occurred in patients treated with pushable coils. MI cases were related to the use of covered stent or stagnant flow after closure of large fistulas (18). In another series of 33 patients, Armsby et al. (4) reported successful closure in 82%. Complications included 5 cases of transient ST-T-wave changes, 4 cases of transient arrhythmia, 1 case of coronary

TABLE 4 Summary of Largest Case Series for Transcatheter Closure of CAF

First Author (Ref. #)	Center	n	Fistula	Devices Used	Follow-Up	Procedural Success	Complications
El-Sabawi et al (18), Jama et al. (8)	Mayo Clinic	45	56	Coils: 40 AVPs: 10 Covered stents: 2 ADOs: 1	Median: 374 days (IQR: 27–2,029 days)	50 (89.3%)	4 MIs, 3 coil embolization, 4 recanalizations of fistula
Armsby et al. (4)	Children's Hospital Boston	35	35	Coils: 28 Umbrella devices: 6 Grifka occluder: 1	Median: 3.7 yrs (IQR: 0.1–11.1 yrs)	30 (86%)	5 ST-T-wave changes, 1 coronary spasm, 1 fistula dissection, 1 coil embolization, 4 transient atrial arrhythmias
Qureshi and Tynan (6)	Guy's Hospital	40	NR	Coils: 45 Balloons: 3 ADO: 1	1 month to 10 yrs	39 (97%)	1 VF arrest, 6 embolizations
Ilkay et al. (33)	Multicenter, Turkey	20	20	Coils: 18 AVPs: 2	Mean: 4 ± 1.6 yrs	20 (100%)	1 AV block
Shah et al. (34)	Toronto General Hospital	25	26		76 months (IQR: 5–214 months)	21 (81%)	2 MIs, 1 coronary dissection, 1 transient ST-segment elevation, 1 coil embolization

ADO = Amplatzer Duct Occluder; AV = atrioventricular; IQR = interquartile range; MI = myocardial infarction; NR = not reported; VF = ventricular fibrillation; other abbreviations as in Table 3.

FIGURE 7 Examples of Myocardial Infarction With Fistula Closure



(A) Coronary angiography in a patient presenting with inferior ST-segment elevation myocardial infarction (STEMI) after successful closure of a distal coronary fistula 3 months prior to presentation revealed disruption of flow to the distal RCA with a large thrombus. **(B)** The patient was treated with balloon angioplasty and thrombectomy. **(C)** Subsequent angiography revealed minimal improvement of flow to the distal vessel. The patient was treated with systemic and then oral anticoagulation. **(D to F)** A case of a 48-year-old woman with complex plexiform fistula originating from the LAD and emptying directly into the left ventricle. The flow into the fistula was terminated with deployment of two 5.0 × 16 mm tandem iCast covered stents. The double-layered stents increase the risk for stent thrombosis. **(E)** The patient presented few days later with anterior STEMI due to stent thrombosis **(red arrow)**. **(F)** The patient was successfully treated with balloon angioplasty and drug-eluting stent placement. **(G to I)** A 45-year-old woman with RCA enlargement and a large fistula originating from the distal segment emptying into the CS. **(G)** Coronary angiography using a 7-F × 45-cm sheath and a 7-F Judkins right 4 guiding catheter demonstrated the tortuous fistula and meshlike origin. **(H)** A Penumbra Pod detachable 8 mm × 60 cm coil was delivered distally through a 2.9-F, 150-cm Lantern microcatheter with controlled deployment. **(I)** Coronary angiography showed complete release of the detachable coil, abolishing flow to the CS. The patient had a mild increase in troponin level after the procedure because of occlusion of a small distal branch **(red arrow)** that was covered with the coil. **(J to L)** A 56-year-old woman with heart failure and a large fistula originating from ectatic LCx (>10 mm in diameter) and emptying into the CS. **(K)** Because of the large size of the fistula, the patient underwent surgical fistula closure without bypassing the distal coronary segments. The patient developed ventricular fibrillation due to inferior STEMI the night of the surgery. **(L)** Coronary angiography revealed thrombotic occlusion of the ectatic LCx **(red arrow)**. Abbreviations as in Figures 2 and 4.

spasm, 1 case of fistula dissection, and 1 case with unretrieved device embolization (4). Studies reporting outcomes of CAF closure are summarized in **Table 4** (4,6,8,18,33,34).

Recanalization of a fistulous tract is a concern for both surgical and transcatheter closure techniques; however, the incidence is unknown, as most patients do not undergo repeat screening imaging. In most published cases, when residual flow is present, it is not hemodynamically significant and does not require repeat intervention. A series of 20 patients who underwent screening CT angiography at 6 months after transcatheter closure found no cases of recanalization (33). In contrast, 4 of 27 fistulas had significant recanalization on repeat angiography at a median of 423 days after transcatheter closure at our institution (18). All of those patients underwent successful reintervention. The higher incidence in the angiographic series may be attributed to a larger sample size, longer duration of follow-up, or differences in imaging modality. We recommend follow-up imaging study with coronary CT angiography or angiography in all patients who underwent successful CAF closure at 1 to 5 years or in patients with recurrent symptoms to evaluate for recanalization.

FUTURE PERSPECTIVES

There are 2 primary challenges to advancing the care of patients with CAFs. First, there is significant heterogeneity in the anatomy, sizes, and flow rates of fistulas. This in turn influences the development and sizes of coronary aneurysms. Large coronary aneurysms are usually associated with large CAFs, likely secondary to long-standing high coronary flow. Still, there are no strong predictors or risk markers to identify fistulas likely to enlarge or lead to hemodynamic consequences over time. Therefore, the optimal timing and role of CAF intervention are not clearly defined. Second, patients present over a wide range of ages, from infancy into late adulthood, and they may have associated comorbidities, including cardiomyopathy, coronary disease, and valvular heart disease, making it difficult to understand the contribution of CAFs to their clinical presentation. Given the complexity of the patient population and the rarity of significant CAF, transcatheter or surgical closures should be performed at experienced tertiary centers. Trials comparing the effects of different treatment options of CAF on morbidity and mortality are impractical. Multicenter registries with long-term clinical and imaging follow-up are therefore needed to help understand the natural history of CAF and the treatment effect of CAF closure compared with conservative management. A comprehensive heart team evaluation should include a pediatric or general cardiologist familiar with the patient and an interventional cardiologist and cardiothoracic surgeon with expertise in fistula closure, taking into account the patient's preferences and comorbidities.

Advances in cardiac imaging can further improve transcatheter closure outcomes by improving preprocedural planning and device selection. Printing of 3-dimensional models can facilitate pre-procedural planning by better defining complex fistula tracts and studying the interaction between devices and patient heart models.

CONCLUSIONS

When clinically indicated, transcatheter closure is an effective treatment for selected medium to large or symptomatic CAFs. Coronary fistulas are anatomically complex and require the use of specialized techniques and equipment. Therefore, these interventions are best performed at tertiary centers with expertise in fistula closure after weighing the anticipated benefits and risks of the procedure. All patients should undergo follow-up coronary imaging to assess for recanalization. Those with large coronary aneurysms are best treated with concomitant surgical bypass and oral anticoagulation to potentially reduce perioperative MI risk.

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ADDRESS FOR CORRESPONDENCE: Dr. Charanjit S. Rihal, Mayo Clinic, Department of Cardiovascular Medicine, 200 First Street SW, Rochester, Minnesota 55905, USA. E-mail: rihal@mayo.edu.

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APPENDIX For supplemental figures, please see the online version of this paper.

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