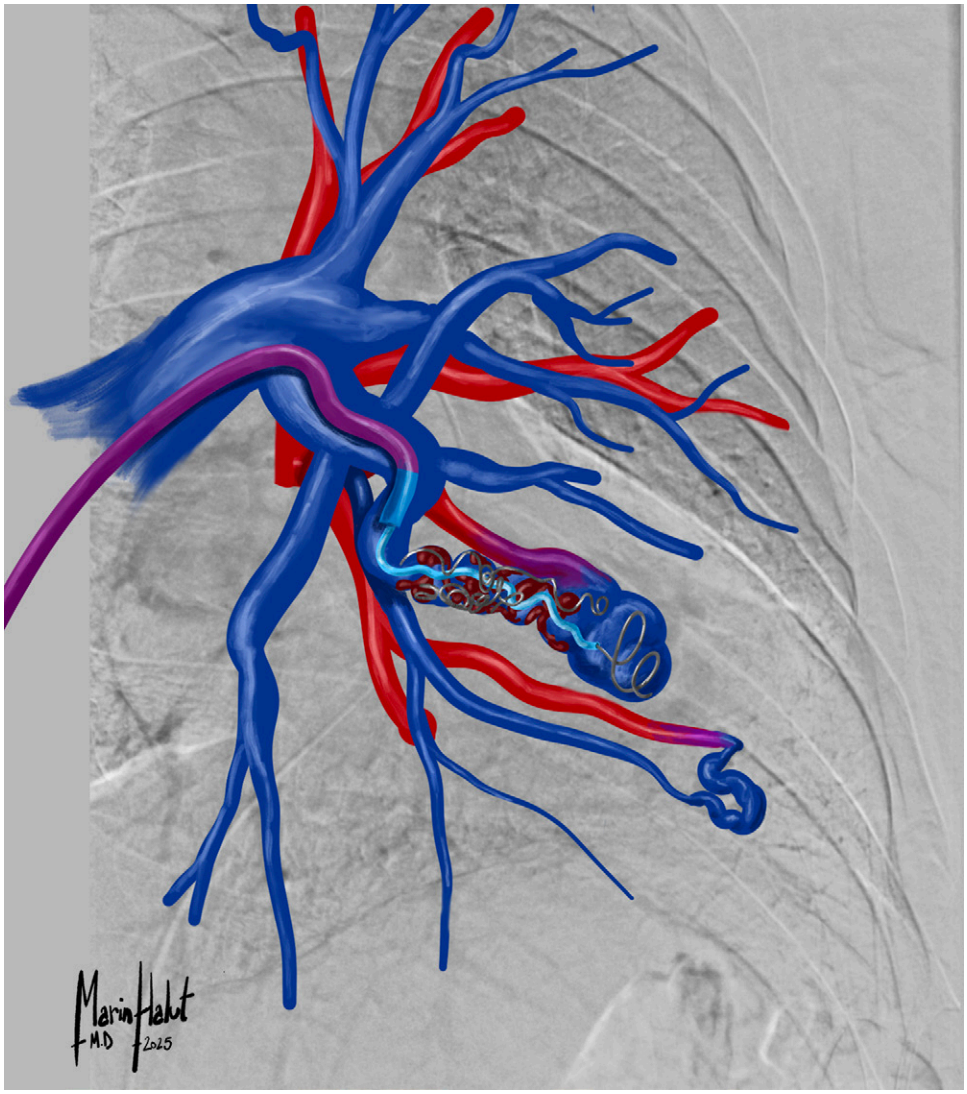
Interventional Management of Pulmonary Arteriovenous Malformations: Imaging Primer

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Pulmonary arteriovenous malformations (PAVMs) are abnormal connections between the pulmonary arteries and veins, bypassing the capillary network and exposing patients to serious complications such as stroke, brain abscess, and hemothorax. The estimated prevalence of PAVMs is approximately one in 2630 individuals, with hereditary hemorrhagic telangiectasia accounting for over 80% of cases. PAVMs are classified as simple, complex, or diffuse based on their angioarchitecture. Diagnostic evaluation involves transthoracic contrast-enhanced echocardiography for screening, chest CT for confirmation, and pulmonary angiography primarily for guiding embolization. Endovascular embolization is the preferred treatment and is typically performed with vascular plugs, although coils may be required for small or tortuous vessels. Postprocedural follow-up with CT is essential to detect persistent or new PAVMs. During pregnancy, PAVMs may enlarge and rupture, significantly increasing complication risks and necessitating close monitoring and treatment. Persistent PAVMs can develop after treatment due to four distinct mechanisms of reopening, each requiring a tailored management approach. The authors provide a comprehensive overview of PAVM angioarchitecture, step-by-step embolization techniques, and a comparative analysis of embolization devices, highlighting their advantages and limitations. Additionally, the authors also discuss follow-up protocols and strategies for managing persistent PAVMs, emphasizing the importance of early detection and timely intervention in preventing severe and potentially life-threatening complications.

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Abbreviations: AVP = Amplatzer Vascular Plug, DSA = digital subtraction angiography, HHT = hemorrhagic telangiectasia, MRA = MR angiography, MVP = Micro Vascular Plug, PAVM = pulmonary arteriovenous malformation, TTCE = transthoracic contrast-enhanced echocardiography

TEACHING POINTS

- The choice of embolic material is critical in PAVM embolization. Plugs and coils are the most commonly used embolic materials due to their effectiveness and safety profile.
- Coils offer better access to smaller, more peripheral, or tortuous PAVMs in comparison with plugs. They allow distal embolization of the arterial feeder and the aneurysmal sac, which may help reduce persistence rates after embolization.
- The outcomes of PAVM embolization, excluding diffuse PAVMs, are generally excellent, as demonstrated in a recent meta-analysis. The treatment success rate of embolization using plugs and/or coils ranges from 86% to 98%, with an immediate technical success rate of 99%.
- The maternal mortality rate associated with PAVMs during pregnancy is estimated at 1%. Given these risks, women with HHT who are considering pregnancy should undergo screening with TTCE and/or CT and any identified PAVMs should be treated before pregnancy.
- By preventing life-threatening complications such as stroke and brain abscess, PAVM embolization plays a critical role in reducing morbidity and mortality, particularly in patients with HHT. When performed rigorously with proper techniques, procedural complications are rare.

Introduction

Pulmonary arteriovenous malformations (PAVMs) are abnormal connections between the pulmonary arteries and veins that bypass the capillary circulation (1,2). The estimated prevalence of PAVMs is approximately one in 2630 individuals (3). These right-to-left shunts can result in life-threatening complications, including stroke, brain abscess, and hemothorax, underscoring the importance of early detection and treatment. The majority of PAVMs (>80%) are associated with hereditary hemorrhagic telangiectasia (HHT), while 20% of the cases are attributed to idiopathic, traumatic, or postsurgical causes, such as the Fontan procedure (2,4,5). HHT is an autosomal dominant hereditary vascular disease with an estimated prevalence of approximately one in 5000 individuals (6). It is caused by mutations in three different genes: *(a)* endoglin *(ENG)* that causes HHT type 1, *(b)* activin receptor–like kinase-1 *(ACVRL1)* that causes HHT type 2, and *(c) SMAD4* that is associated with an overlapping syndrome of HHT and juvenile polyposis (6).

A definitive diagnosis of HHT can be made when at least three of the four Curaçao criteria are present: *(a)* recurrent epistaxis, *(b)* mucocutaneous telangiectasia, *(c)* visceral arteriovenous malformations, and *(d)* a positive family history. Genetic HHT testing is recommended for all patients with one or more PAVMs and can confirm the diagnosis in cases where clinical criteria are inconclusive (7). Approximately 50% of patients with HHT have PAVMs detectable at CT (8). Early detection and management of PAVMs are crucial for preventing complications that could lead to severe life impairment.

Clinical Manifestations of PAVM

Today, PAVMs are more frequently identified incidentally at imaging conducted for unrelated reasons rather than diagnosed due to clinical manifestations. While often found in asymptomatic patients, PAVMs can lead to three primary clinical manifestations (9), as shown in Figure 1.

First, the lack of capillary vascular filtration allows thrombi, bacteria, and vasoactive substances to enter in the systemic arterial circulation (2,10). Paradoxical thromboembolism can lead to stroke, transient ischemic attack, or myocardial infarction (8), while bacterial entry into the systemic circulation may result in cerebral and peripheral abscesses (11). Finally, the release of vasoactive substances into the cerebral circulation can trigger migraines (2).

Second, the high-flow right-to-left shunt can result in hypoxemia, dyspnea, increased ventilation, and elevated cardiac output, with severity correlating to the size of the shunt (1,8). Finally, the rupture of thin-walled PAVMs can result in hemoptysis or hemothorax (12).

The most common symptoms of HHT include recurrent epistaxis, which affects 95% of patients by age 21 years, and telangiectasia, which is present in 95% of patients by age 30 years (13) (Fig 2). Gastrointestinal telangiectasia can cause bleeding and anemia while symptoms related to arteriovenous malformations vary depending on their anatomic localization (brain, spine, and liver). HHT demonstrates age-dependent penetrance, with symptoms in children often being subtle (7,8).

PAVM Angioarchitecture Classification

PAVMs are classified into three categories: simple, complex, and diffuse. In 1983, White et al (14) introduced an angiographic classification that differentiates between simple and complex PAVMs based on the number of arterial feeders (Fig 3). A simple PAVM, comprising approximately 80% of cases, was defined as a single pulmonary artery connected to an aneurysmal sac with a single pulmonary draining vein. In contrast, a complex PAVM (20%) involves an aneurysmal sac fed by two or more pulmonary arteries. Diffuse PAVMs are rare, accounting for less than 5% of all PAVMs, and are characterized by the diffuse involvement of a segment, a lobe, or an entire lung (14–16). This last category is proportionally more common in pediatric patients, accounting for up to 29% of PAVMs in this population (17).

In 1996, White et al (15) updated this classification to provide a more detailed understanding (18) (Fig S1). In the revised classification, a PAVM is considered simple if it is supplied by a single segmental artery, regardless of the number of subsegmental feeders, and complex if it is supplied by two or more segmental arteries. The definition of diffuse PAVM remained the same.

The 1983 and 1996 classifications are still in use, although their application varies by authors and geographic regions, leading to some inconsistency. The 1983 classification remains the most widely used, particularly in clinical studies (1,5,19–26), and it is the classification we use at our institution due to its simplicity in a daily practice.

The final type of PAVM is the telangiectatic PAVM, which are lesions that appear as ground-glass nodules at chest CT

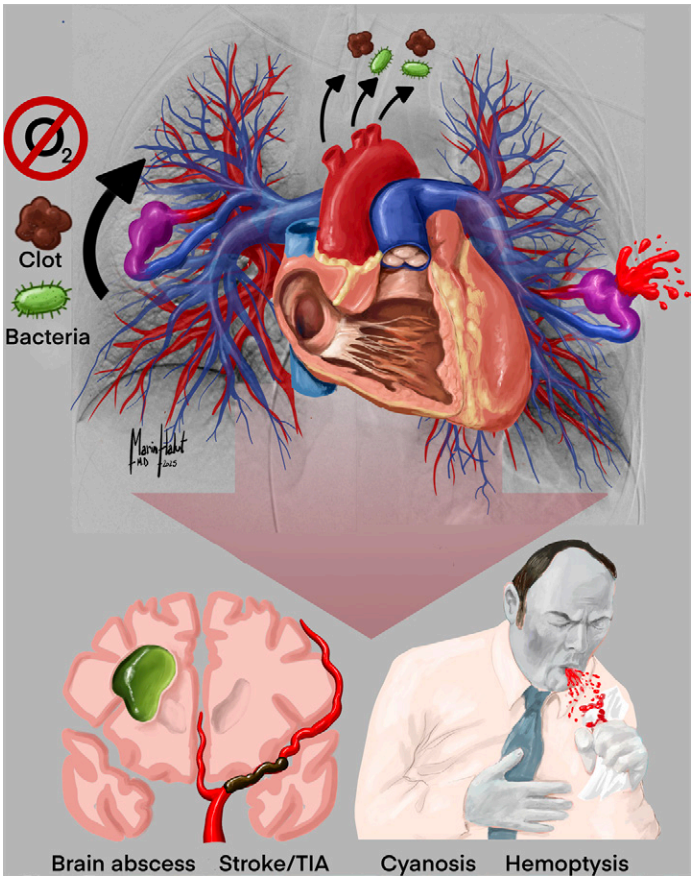


Figure 1. Illustration depicts the anatomic and pathologic mechanisms leading to clinical manifestations and complications of PAVMs. *TIA* = transient ischemia shock.

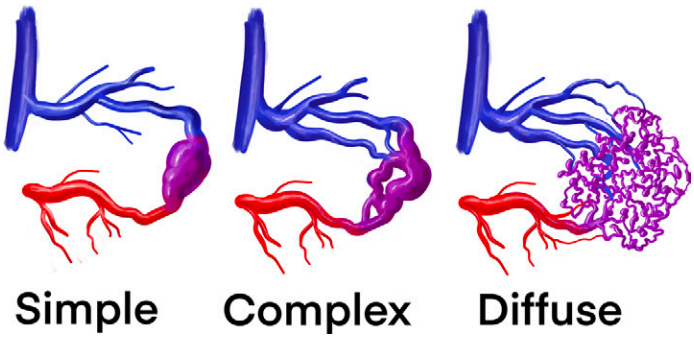


Figure 3. Illustration shows the classification developed by White et al (14). The first version of the classification was published in 1983, with a simple PAVM corresponding to a direct aneurysmal connection between a single pulmonary artery and draining pulmonary vein. Complex PAVM corresponds to multiple pulmonary arteries, leading to a septated aneurysmal bag with multiple draining pulmonary veins. Diffuse PAVM was later described as PAVM completely involving an entire segment, lobe, or lung.

and may be accompanied by micronodular thickening within the lesion (27) (Fig 4). Some authors suggest that these ground-glass nodules represent the earliest stage of PAVM development, consisting of microscopic arteriovenous connections (28,29). There is some overlap with diffuse PAVMs, as they can exhibit a telangiectatic component (14).

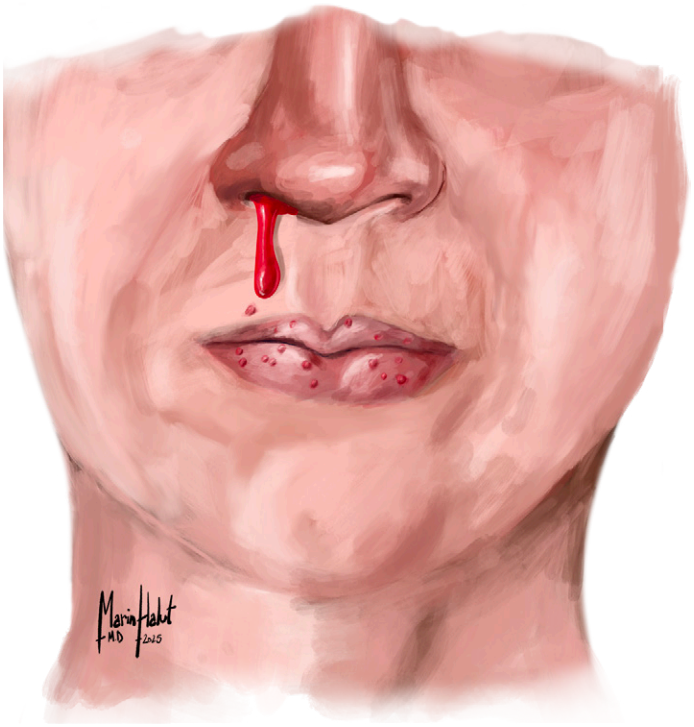


Figure 2. Illustration shows a patient with mucosal telangiectasia of the lips and skin and with active epistaxis.

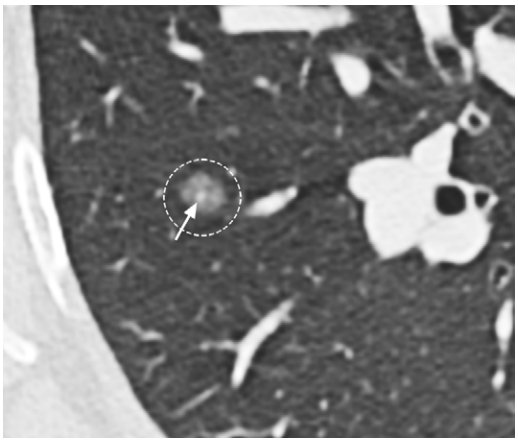


Figure 4. Telangiectatic PAVM in a 37-year-old woman with HHT. Axial non–contrast-enhanced chest CT image shows a 9-mm diameter ground-glass nodule (circle) in the right lower lobe. Also shown is a central dense focus corresponding to a tiny pulmonary venous branch (arrow).

In a recent study of 312 PAVM embolizations, 32.7% were located in the right lower lobe, 30.8% in the left lower lobe, 11.2% in the middle lobe, 11.5% in the right upper lobe, and 13.9% in the left upper lobe (26).

Imaging Evaluation

Transthoracic Contrast-enhanced Echocardiography

Transthoracic contrast-enhanced echocardiography (TTCE) is the recommended screening tool for PAVMs in patients

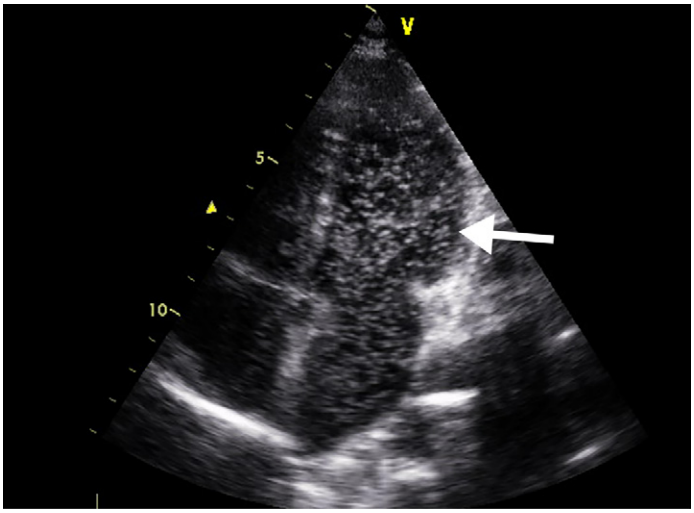


Figure 5. Right-to-left shunt in a 14-year-old adolescent girl with HHT who was referred for PAVM screening. TTCE image shows a microbubble appearance (arrow) in the left ventricle after six cardiac cycles that indicates an extracardiac right-to-left shunt. Subsequent chest CT confirmed the presence of multiple PAVMs.

with HHT (30). This test does not allow direct visualization of the PAVMs. Rather, it is used to detect the right-to-left shunt secondary to the PAVM. A right-to-left shunt at TTCE is identified by the appearance of microbubbles in the left ventricle after intravenous injection of agitated saline (Fig 5). Differentiation between pulmonary and intracardiac shunts is made by direct visualization of the shunt origin, such as an atrial or ventricular septal defect, or by assessing the delay in microbubble appearance between the right and left ventricles if the shunt origin is not visible. A shunt is considered intracardiac if bubbles appear in the left ventricle within two cardiac cycles (27,31). The number of cardiac cycles used to define a pulmonary right-to-left shunt varies across studies. van Gent et al (32) used a threshold of four cardiac cycles and reported a sensitivity of 97%, specificity of 77%, negative predictive value of 99%, and positive predictive value of 51% for detecting PAVMs. Regardless of timing, if microbubbles are observed entering the left atrium through the pulmonary veins, the shunt is considered pulmonary (31).

When microbubbles appear in the left atrium after a delay of 2–3 cardiac cycles without clear visualization of the shunt origin, the result is considered indeterminate, and further evaluation with transesophageal echocardiography or chest CT is recommended. Since a patent foramen ovale may not be detectable at rest, TTCE with the Valsalva maneuver is often required to reveal the shunt (31).

Right-to-left shunts can also occur in hepatopulmonary syndrome, pulmonary sequestrations, unroofed coronary sinus, and certain congenital heart defects treated with cavopulmonary anastomosis (eg, Glenn procedure) (27,31). This surgery may eventually lead to the formation of PAVMs with right-to-left shunt. Additionally, small pulmonary shunts have been observed at TTCE in a subset of healthy individuals (31).

Computed Tomography

In patients with HHT and a positive TTCE, or if TTCE is unavailable, current international guidelines recommend non–contrast-enhanced multidetector thorax CT with thin-cut 1–2-mm reconstructions (30). The absence of an iodinated contrast agent eliminates the risk of intravascular air embolism, making it particularly beneficial for patients who may be at risk for paradoxical embolism. Postprocessing techniques with maximum intensity projection reconstructions facilitate the identification of PAVMs (33). A PAVM typically appears as a pulmonary nodule or serpiginous mass with a feeding pulmonary artery and a draining pulmonary vein, both of which are often enlarged (Fig 6). Additionally, ultra–low-dose chest CT has demonstrated diagnostic performance comparable to that of conventional CT while reducing radiation. Non–contrast-enhanced CT findings provide diagnostic accuracy comparable to that of CT pulmonary angiography findings due to the inherent natural contrast between the pulmonary vessels and lung parenchyma (34). Nevertheless, CT pulmonary angiography is superior for visualizing PAVM angioarchitecture and for excluding lesions that mimic PAVM (27). Precautions must be taken to prevent paradoxical air embolism during intravenous contrast agent injection, such as using an intravenous line filter (30,34).

Magnetic Resonance Imaging

MR angiography (MRA) of the pulmonary arteries with intravenous contrast agent is a viable imaging modality for the detection of PAVMs. However, its relatively low spatial resolution may limit the detection of PAVMs that are smaller than 5 mm (34). A recent study in a pediatric population reported that MRA can be used to detect PAVMs with arterial feeders that are 2 mm or larger, with a sensitivity of 92%–97% and specificity of 62%–92% (35). The primary advantage of MRA is the absence of radiation exposure, which is especially important in pediatric patients. However, the potential to miss smaller PAVMs is a significant concern, as complications can arise from lesions smaller than 3 mm (36). Gadolinium contrast agent–enhanced MRA with time-resolved sequences has been shown to be superior to non–contrast-enhanced CT for the detection of persistent PAVMs after embolization, as it is less affected by artifacts from embolization materials. (37,38). Non–contrast-enhanced MRA has no role in the evaluation of PAVMs (34).

Pulmonary Angiography

Pulmonary angiography is rarely used for PAVM detection, although it can sometimes help to differentiate lesions that mimic PAVMs at CT (Fig 7). Selective pulmonary angiography is primarily used to guide PAVM embolization. Although pulmonary angiography has traditionally been considered the reference standard for characterizing PAVMs, it is less sensitive than CT and may fail to detect reperfusion through the systemic arteries, such as bronchial or transpleural collaterals (34,39).

Indication and Preprocedural Preparation

All treatable PAVMs should be embolized if technically feasible, regardless of the size (9). Historically, PAVMs with feeding pulmonary arteries smaller than 3 mm were considered low

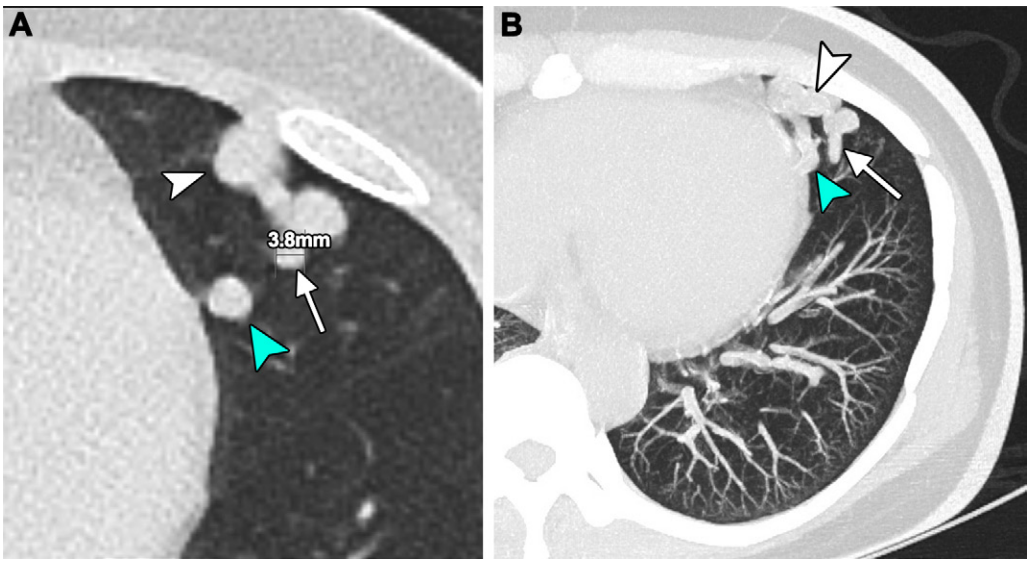


Figure 6. PAVM in a 47-year-old man with HHT and positive TTCE. Axial CT image **(A)** and axial maximum intensity projection CT reconstruction **(B)** show a simple PAVM located in the lingula with a single feeding artery (arrow), an aneurysmal sac (white arrowhead), and an enlarged draining vein (blue arrowhead).

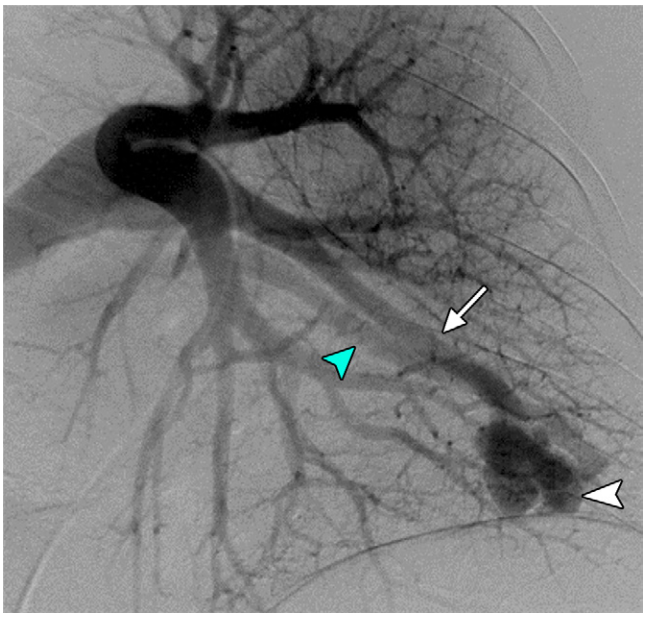


Figure 7. PAVM in a 67-year-old woman with HHT. Digital subtraction angiographic (DSA) image of the left pulmonary artery shows a simple PAVM in the left lower lobe with a single feeding artery (arrow), an aneurysmal sac (white arrowhead), and an enlarged draining vein (blue arrowhead).

risk and did not require treatment (11,40). However, this approach is no longer supported as stroke and brain abscess have been documented in cases of PAVMs smaller than 3 mm (36,40).

Preprocedural electrocardiography is mandatory for the detection of left bundle branch block (LBBB) as device manipulation in the right ventricle during embolization can induce right bundle branch block, potentially leading to complete atrioventricular block and cardiac arrest. For patients with preexisting LBBB, placement of a temporary transvenous pacemaker is recommended to mitigate this risk (11).

A bladder catheter or urinary condom catheter is suggested for prolonged embolization sessions to treat multiple PAVMs. Antibiotic prophylaxis is generally not recommended (9), although some centers advocate its use based on institutional protocols or specific clinical scenarios. The Cardiovascular and Interventional Radiologic Society of Europe guidelines recommend systemic anticoagulation therapy with heparin at a dose of 100 IU/kg or 3000–5000 IU and maintaining an activated clotting time of approximately 200 seconds to reduce the risk of clot formation and potential paradoxical embolization (9). However, the level of evidence supporting this recommendation is low, and some centers choose not to use systemic anticoagulation therapy due to the risk of bleeding complications in the already high-risk HHT population (26). Relative contraindications to embolization include uncorrectable coagulopathy, contrast agent–induced anaphylaxis, and severe pulmonary hypertension (Table).

Embolization Devices

The choice of embolic material is critical in PAVM embolization. Plugs and coils are the most commonly used embolic materials due to their effectiveness and safety profile. Particles are prohibited and all liquid embolic agents should be avoided, as they pose a high risk of migration through the shunt, even when an occluding balloon is used (41). The decision to use plugs or coils depends on the diameter, length, and tortuosity of the feeding artery, as well as the level of difficulty in accessing it.

Bare Metal Plugs

The Amplatzer Vascular Plug (AVP; Abbott Cardiovascular) is widely used for occluding large PAVMs and offers precise and controlled deployment. Oversizing AVPs by 30%–50% relative to the artery diameter is recommended (42). While fourth-generation AVPs (diameter, 4–8 mm) allow embolization of feeding arteries of up to 6 mm through a 4F or 5F 0.038-inch catheter, larger AVPs (first- and second-generation AVPs, 3–22 mm) require a larger guiding catheter, which may be difficult to navigate in tortuous or hard-to-reach feeding arteries. PAVM persistence rates after embolization with AVPs range from 5% to 8%, which are lower than rates after coil-only embolization (20,25,26,43–45).

Tips to Avoid Common Pitfalls in PAVM Embolization

Tip	Avoided Pitfall
Perform electrocardiography before the procedure	Prevents complete heart block in patients with left bundle branch block
Use saline perfusion with an intravenous filter on the sheath's side port	Prevents thrombus or air bubble migration
Use a pigtail catheter to cross valves in the right ventricle	Prevents injury to cardiac structures from guidewires or diagnostic catheters
Inject a small amount of saline through the three-way stopcock while withdrawing the guidewire, diagnostic catheter, or plug pusher	Prevents vacuum-induced air bubbles
Shape the distal tip of the hydrophilic microguidewire into a J shape	Facilitates access to the PAVM feeding artery and prevents pulmonary artery perforation
Use a Rosen or Bentson guidewire instead of a hydrophilic guidewire in the pulmonary arteries	Prevents pulmonary artery perforation and hemothorax
Advance the guiding catheter cautiously into the aneurysmal sac	Prevents perforation of the aneurysmal sac
In large feeding arteries, plugs are preferred instead of coils	Prevents coil migration
Oversize the AVP by 30%–50% relative to the feeding artery diameter	Prevents AVP migration
Oversize the coil by 30%–50% when embolizing the aneurysmal sac	Prevents coil migration
Use soft coils rather than rigid coils	Prevents aneurysmal sac perforation
Gently inject iodinated contrast agent through the guiding catheter before detaching the plug	Confirms positioning and evaluates vessel occlusion
After placing the first coil or plug, gently inject contrast agent through the guiding catheter	Prevents thrombus migration from within the coil nest or AVP lobes
Occlude the feeding artery as close as possible to the aneurysmal sac (or embolize the sac itself)	Prevents reperfusion from systemic arterial collaterals, which are difficult to embolize and pose bleeding risks

Membrane-assisted Plugs

The Micro Vascular Plug (MVP; Medtronic) system features a nitinol cage covered with polytetrafluoroethylene (PTFE) and radiopaque markers for precise positioning and immediate occlusion (21). The MVP 3Q and 5Q can be delivered through 0.021- and 0.027-inch microcatheters, respectively, and may be used to occlude PAVM feeding arteries that range from 1.5 to 5 mm, making it ideal for small tortuous vessels (21). The MVP 7Q and 9Q are delivered through 4F and 5F guiding catheters and can occlude PAVM feeding arteries between 5 and 9 mm. Unlike AVPs, MVPs should not be oversized, as full expansion of the PTFE membrane is required for effective occlusion (21). Although long-term data are limited, the MVP system has demonstrated a low PAVM persistence rate after embolization of 0%–6% (21,45–47).

The Azur vascular plug (Terumo Medical) is a newer device that features a dynamic occlusive membrane within a nitinol cage. However, clinical experience with this device for PAVM embolization remains limited, and further studies are needed to assess its efficacy and safety in this setting.

Most vascular plugs can be resheathed and repositioned if placement is unsatisfactory. However, care should be taken to minimize the embolization device dwelling time before repositioning to prevent thrombus formation that could migrate while the device is resheathed.

Coils

Coils offer better access to smaller, more peripheral, or tortuous PAVMs in comparison with plugs (48). They allow distal embolization of the arterial feeder and the aneurysmal sac, which may help reduce persistence rates after embolization (48–52). The first coil deployed should have a diameter of 20% or 2 mm larger than the embolized vessel to ensure proper occlusion (9). Detachable coils have been proposed as a safer alternative to pushable coils for PAVM embolization as they allow controlled packing and reduce the risk of nontarget embolization and coil migration. However, there is also a risk of detachable coil migration during embolization (53). PAVM persistence rates after embolization with coils range from 11.7% to 34.1%, which is significantly higher than those after embolization with plugs (20,26,45,54,55).

Detachable Fibered Coils.—Detachable fibered 0.018-inch coils accelerate vessel occlusion due to their increased thrombogenicity (48,56). However, despite accelerated occlusion, studies have not demonstrated a lower PAVM persistence rate after embolization compared with nonfibered coils (26).

Detachable Hydrogel-coated Coils.—Detachable hydrogel-coated 0.018-inch coils expand within 20 minutes of blood contact, providing greater cross-sectional vessel occlusion with less reliance on thrombus formation. Clinical studies reported no persistence after PAVM embolization with hydrogel-coated coils (53,57). However, it remains unclear whether the absence of persistence is attributable to the hydrogel-coated coils themselves or to the aneurysmal sac embolization performed in one of these studies (53). Hydrogel-coated coils also have the

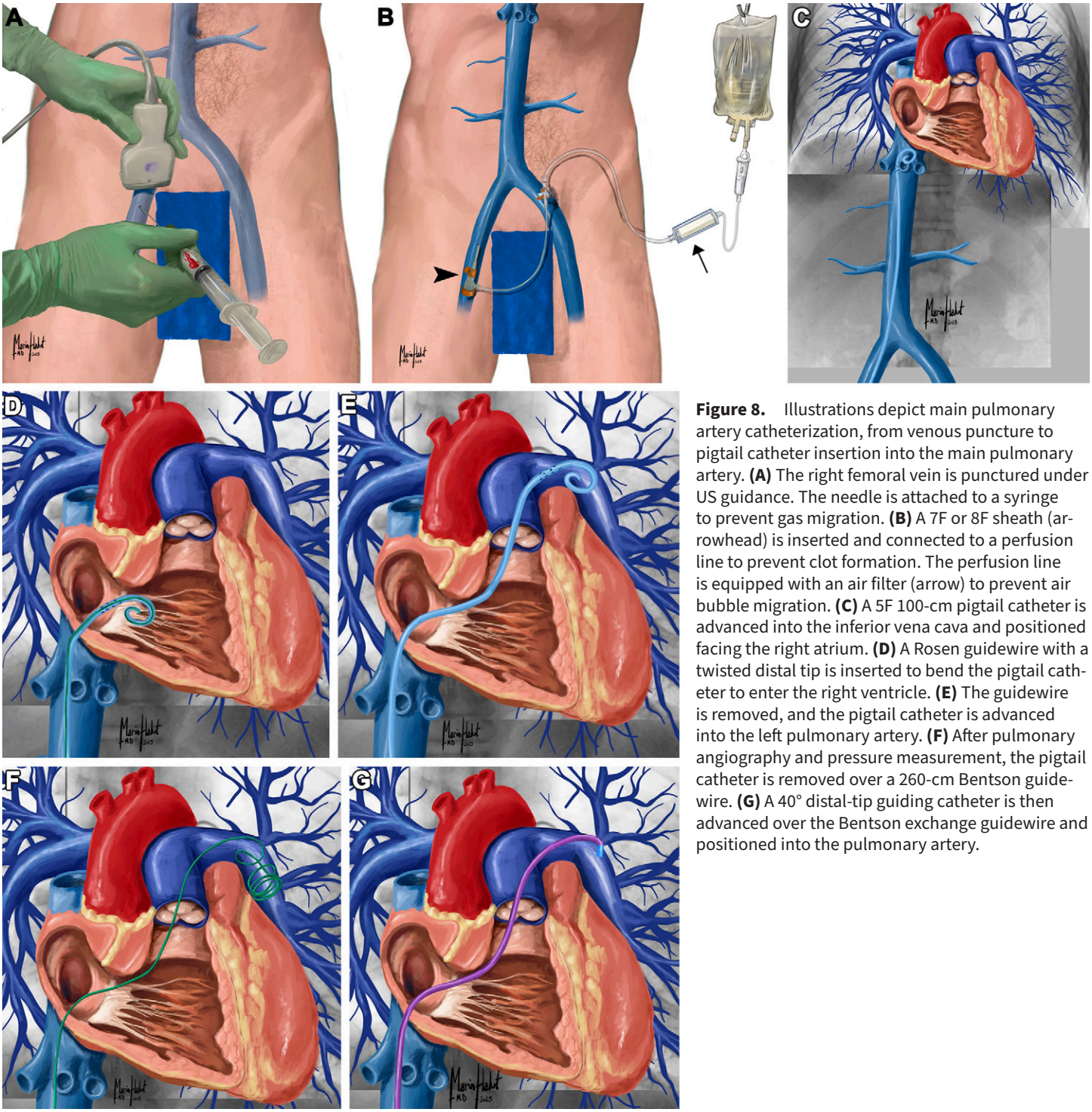


Figure 8. Illustrations depict main pulmonary artery catheterization, from venous puncture to pigtail catheter insertion into the main pulmonary artery. **(A)** The right femoral vein is punctured under US guidance. The needle is attached to a syringe to prevent gas migration. **(B)** A 7F or 8F sheath (arrowhead) is inserted and connected to a perfusion line to prevent clot formation. The perfusion line is equipped with an air filter (arrow) to prevent air bubble migration. **(C)** A 5F 100-cm pigtail catheter is advanced into the inferior vena cava and positioned facing the right atrium. **(D)** A Rosen guidewire with a twisted distal tip is inserted to bend the pigtail catheter to enter the right ventricle. **(E)** The guidewire is removed, and the pigtail catheter is advanced into the left pulmonary artery. **(F)** After pulmonary angiography and pressure measurement, the pigtail catheter is removed over a 260-cm Bentson guidewire. **(G)** A 40° distal-tip guiding catheter is then advanced over the Bentson exchange guidewire and positioned into the pulmonary artery.

disadvantage of being rigid, which may lead to sac perforation during coil delivery (53,57). Furthermore, if the coil is repositioned after it has remained in the vessel for some time, it may get stuck in the catheter.

Detachable Platinum Coils.—Detachable platinum 0.018- and 0.035-inch coils achieve occlusion solely through mechanical blockage and must be densely packed to ensure effective vessel closure (48). Today, 0.035-inch coils have largely been replaced by vascular plugs for large PAVMs and by 0.018-inch coils for smaller ones.

Embolization Technique

Although techniques may vary across institutions, the procedure used at the authors' center begins with thorough skin disinfection, sterile draping, administration of local anesthesia, and light intravenous sedation. The femoral vein is punctured with US guidance. If an inferior vena cava (IVC) filter is present or in cases of IVC occlusion, the jugular vein can also be accessed (58). To prevent gas migration into the vein, a syringe should be connected to the puncture needle (Fig 8A). A 7F or 8F sheath is then inserted, corresponding to the diameter of the guiding catheter

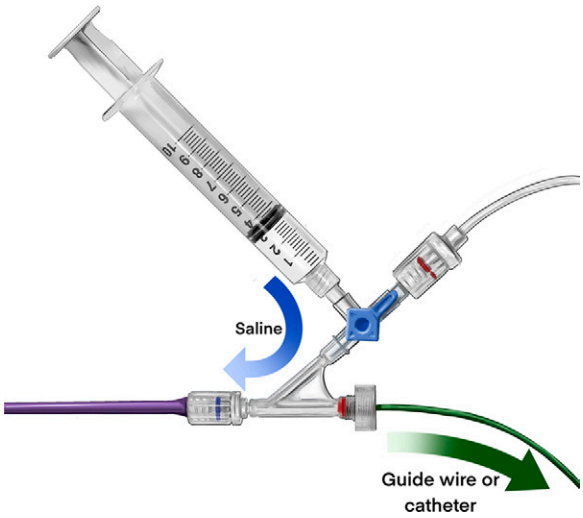


Figure 9. Illustration depicts the Y-connector and three-way stopcock setup. As the guidewire or catheter is withdrawn from the guiding catheter, saline is manually injected through the three-way stopcock to prevent the formation of vacuum-induced gas bubbles.

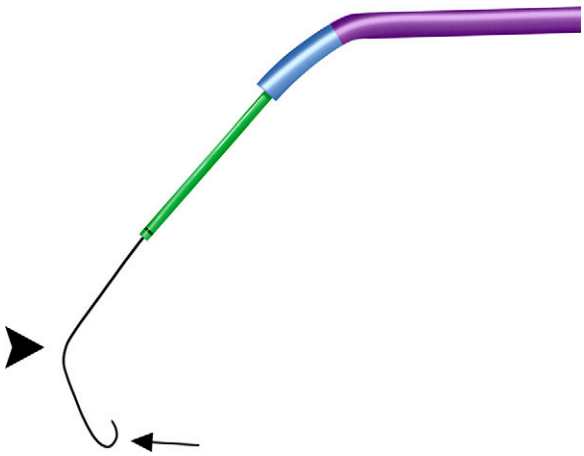


Figure 10. Illustration depicts a manually shaped Transend microguidewire featuring a tight distal J curve (arrow) to follow the main path to the PAVM feeder and to reduce the risk of perforation, along with a second more proximal curve (arrowhead) for steering the guidewire.

required for embolization device insertion. To prevent air bubbles or thrombus migration and reduce the risk of paradoxical embolization, a saline drip with an air filter is attached to the side port of the sheath (Fig 8B).

A 5F 100-cm pigtail catheter is advanced into the IVC and positioned just below the right atrium (Fig 8C; Movie 1). The distal hard portion of the Rosen guidewire, just proximal to the floppy tip, is manually shaped to form a 360° loop. When the Rosen guidewire is introduced into the pigtail catheter, its curve tilts the catheter tip, allowing for a safe passage across the tricuspid valve and entry into the right ventricle (Fig 8D; Movie 1). The guidewire is then pulled back, allowing the pigtail catheter to be advanced into the pulmonary trunk and subsequently into the left main pulmonary artery (Fig 8E; Movie 1). Once the catheter is positioned in the left main pulmonary artery, pulmonary pressure is measured. Alternatively, an angulated pigtail catheter, such as the Grollman pigtail catheter, can be used to access the right ventricle (25).

Access to the right pulmonary artery requires making a sharp turn. This is achieved by readvancing the twisted Rosen guidewire to reshape the pigtail catheter tip. The catheter and guidewire are pulled back together to the bifurcation, rotated toward the right side, and advanced into the right pulmonary artery (Movie 1). Pulmonary arteriography is performed at a frame rate of 3–10 frames/sec using an injection rate of 10–15 mL/sec for 2 seconds, with an anterior-posterior view and a 35° contralateral anterior-oblique view for each pulmonary artery.

The pigtail catheter is then exchanged over a Bentson exchange guidewire for a 40° distal-tip guiding catheter (7F or 8F; 90 cm), such as the Guider SoftTip XF (Boston Scientific) (Fig 8F, 8G; Movie 2). A Y-connector is attached to the guiding catheter, with a continuous saline infusion line in place. Additionally, saline is manually injected through a three-way stopcock whenever a catheter or guidewire is withdrawn, preventing the formation of vacuum-induced gas bubbles (Fig 9).

Simple PAVM Embolization with Bare Metal Plugs

To catheterize a PAVM, a 0.014-inch shapeable hydrophilic-tip guidewire such as the Transend (Boston Scientific) is initially used. The guidewire is manually shaped using a needle to create a tight distal J curve, which helps the guidewire remain in the main channel that leads to the PAVM while minimizing the risk of perforation. Additionally, a second more proximal curve is created to facilitate in steering the guidewire (Fig 10). If the tight J shape is not created, the hydrophilic guidewire (0.014 or 0.035 inches) should be handled with extreme care because it could easily perforate the distal pulmonary arteries.

The tight J-shaped 0.014-inch Transend microguidewire is carefully advanced into the aneurysmal sac (Fig 11A–11C). The guiding catheter can then be advanced directly over the guidewire or with the help of a 4F catheter when additional support is needed (Fig 11D). To minimize trauma to the arterial walls, the guiding catheter is gently advanced while its 40° distal tip is steered toward the vessel supplying the PAVM. The catheter is positioned as far as possible into the arterial feeder or, if possible, inside the aneurysmal sac. Caution should be taken to avoid perforation of the thin-walled PAVM aneurysmal sac with the guiding catheter. Thus, the 0.014-inch guidewire is kept beyond the catheter tip as a bumper, preventing sac perforation when the guiding catheter is displaced due to breathing movements. The guidewire is removed just before inserting the plug, which should be prepared in advance before cannulation of the PAVM sac.

A second-generation AVP (or a first-generation AVP in cases of a short feeding artery) is deployed, with the first lobe positioned within the aneurysmal sac. The guiding catheter is then gently retracted to allow the deployment of the remaining two lobes within the feeding artery by unsheathing the plug (Fig 11E; Movie 3). Before detachment, contrast agent is slowly injected manually to assess proper plug positioning and confirm occlusion (Fig 11F). A gentle injection is necessary to prevent dislodging fresh thrombus.

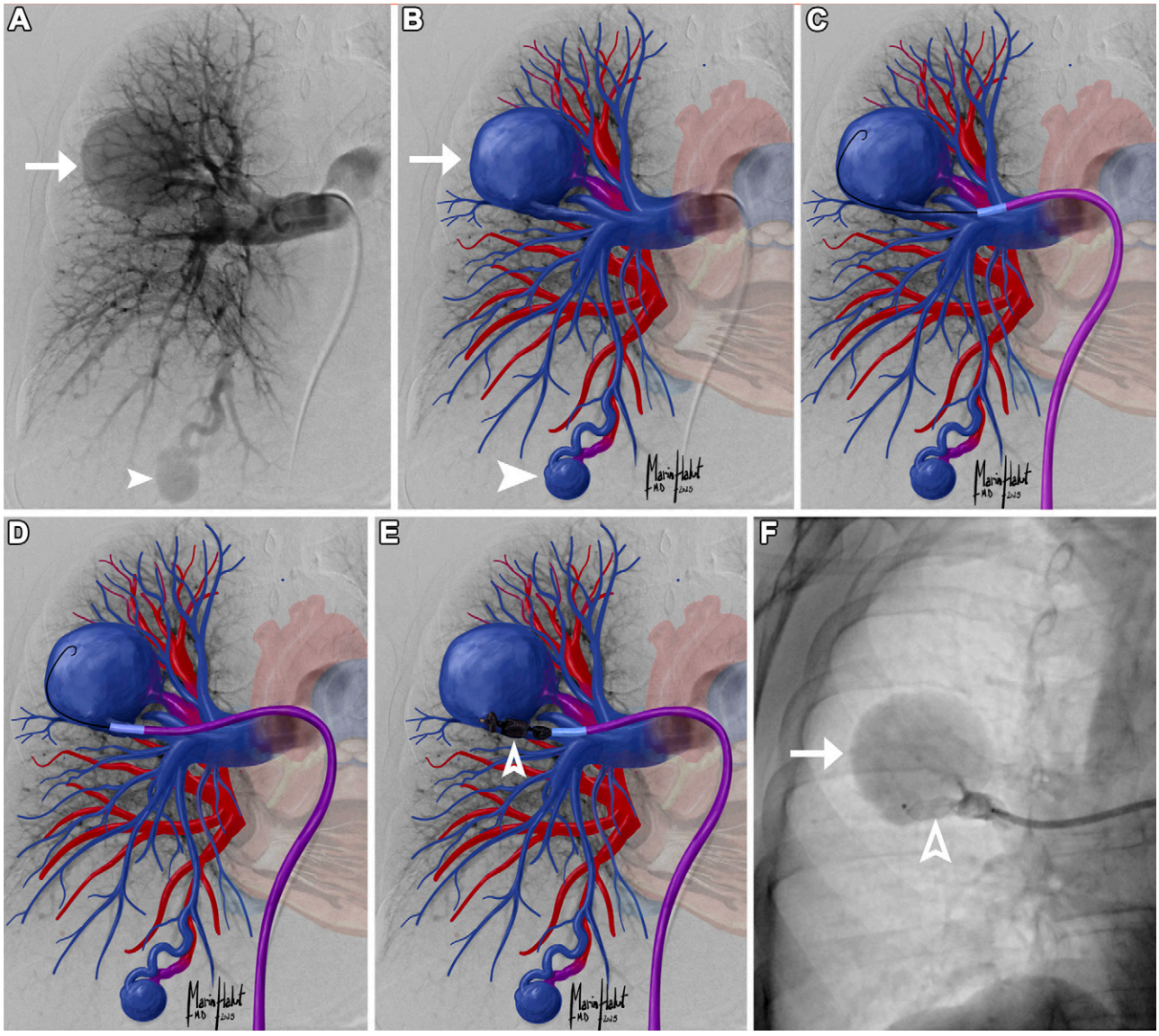


Figure 11. PAVMs in HHT in a 66-year-old woman with a history of stroke. **(A)** DSA image of the right pulmonary artery shows a simple PAVM in the right upper lobe (arrow). A second simple PAVM is seen in the right lower lobe (arrowhead). **(B)** Illustration based on the previous angiogram shows the connection between the arteries and veins of the upper lobe PAVM (arrow) and of the lower lobe PAVM (arrowhead). **(C)** Illustration shows the manually shaped microguidewire advanced within the PAVM. **(D)** Illustration shows the guiding catheter slightly advanced within the aneurysmal sac. **(E)** Illustration shows embolization of the PAVM with an AVP (arrowhead). **(F)** Fluoroscopic image shows PAVM embolized with the AVP (arrowhead) and stagnant contrast agent within the PAVM (arrow).

If vessel tortuosity prevents the guiding catheter from advancing, the patient is instructed to take a deep breath and hold it. Deep inspiration straightens the vessels, facilitating the advancement of the guiding catheter closer to the aneurysmal sac (Fig 12; Movie 4). When vessel tortuosity remains a challenge, a 4F or 5F catheter and a microcatheter in a triaxial configuration may help the guiding catheter reach the distal arterial feeder. If the guiding catheter still fails to reach the arterial feeder, embolization is performed using the microcatheter, with an MVP or 0.018-inch detachable coils.

Simple PAVM Embolization with Membrane-Assisted Plugs

The guiding catheter is advanced as close as possible to the aneurysmal sac, with or without the assistance of a 4F or 5F catheter in a more supportive triaxial configuration. A microcatheter and a J-shaped Transend guidewire are then used to catheterize the distal arterial feeder as close as possible to the aneurysmal sac (Fig 13; Movie 5).

The MVP is deployed in the arterial feeder and positioned as close as possible to the aneurysmal sac. The arterial feeder diameter is measured, and the MVP size is selected to match accordingly. The plug is deployed by unsheathing the microcatheter while maintaining pressure on the plug wire (Fig 13; Movie 5). A gentle injection of contrast agent through the guiding catheter ensures proper positioning and occlusion before detaching the plug. Alternatively, if vessel tortuosity prevents MVP delivery, embolization is performed using 0.018-inch detachable coils in the arterial feeder and the aneurysmal sac.

Figure 12. Illustrations show how to straighten and catheterize a tortuous PAVM feeding artery. **(A)** The arterial feeder is too tortuous, preventing further advancement of the guiding catheter. **(B)** The patient is asked to take a deep breath and hold it, which straightens the vessels. This vessel straightening facilitates the distal advancement of the guiding catheter within the arterial feeder. **(C)** The PAVM is successfully embolized using an AVP.

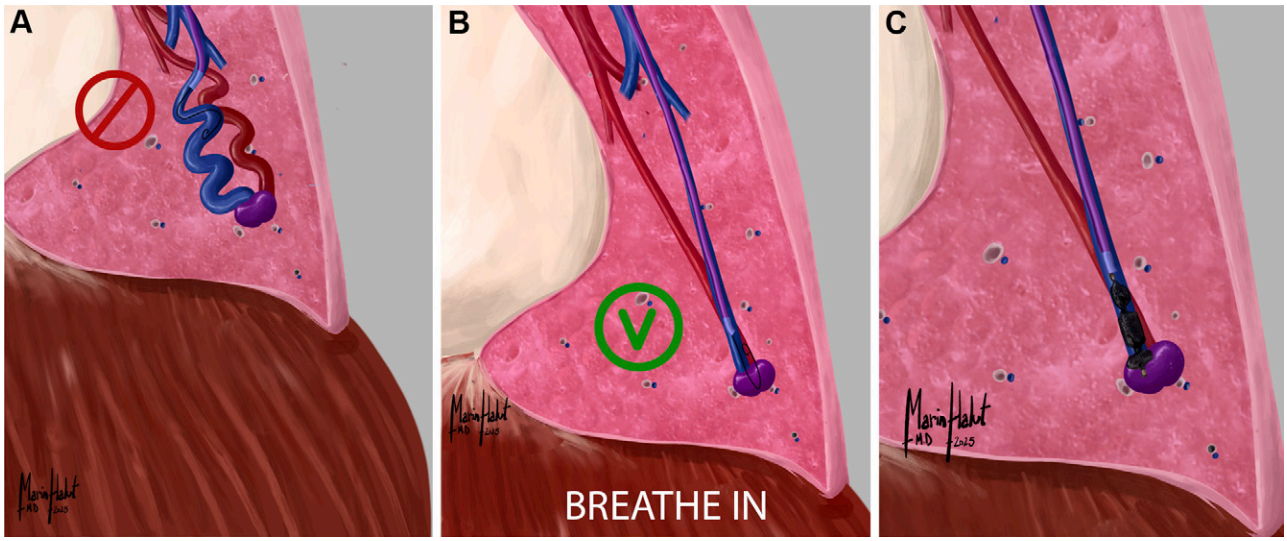
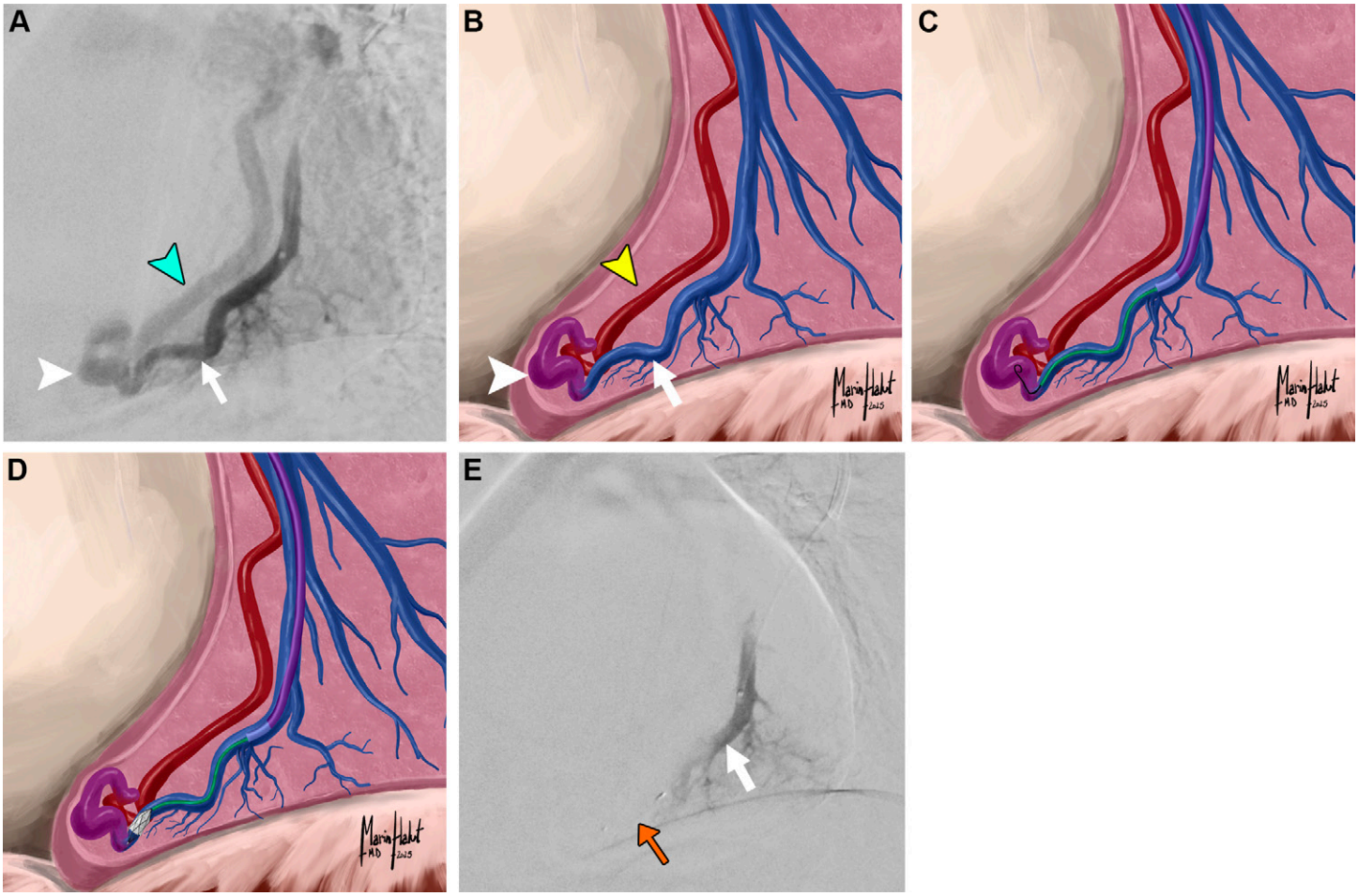


Figure 13. Idiopathic simple PAVM in a 39-year-old woman without clinical symptoms. **(A)** Selective DSA image of a left lower lobe pulmonary artery shows a PAVM with a single feeding artery (arrow) supplying an aneurysmal sac (white arrowhead) with a single draining vein (blue arrowhead). **(B)** Illustration based on the previous angiogram shows the PAVM (white arrowhead), feeding artery (arrow), and draining vein (yellow arrowhead). **(C)** Illustration depicts the guidewire within the PAVM and the microcatheter positioned into the distal portion of the feeding artery. **(D)** Illustration shows the deployment of MVP within the distal segment of the feeding artery by unsheathing the microcatheter. **(E)** Postembolization DSA image confirms complete occlusion of the PAVM (white arrow) with MVP (orange arrow).



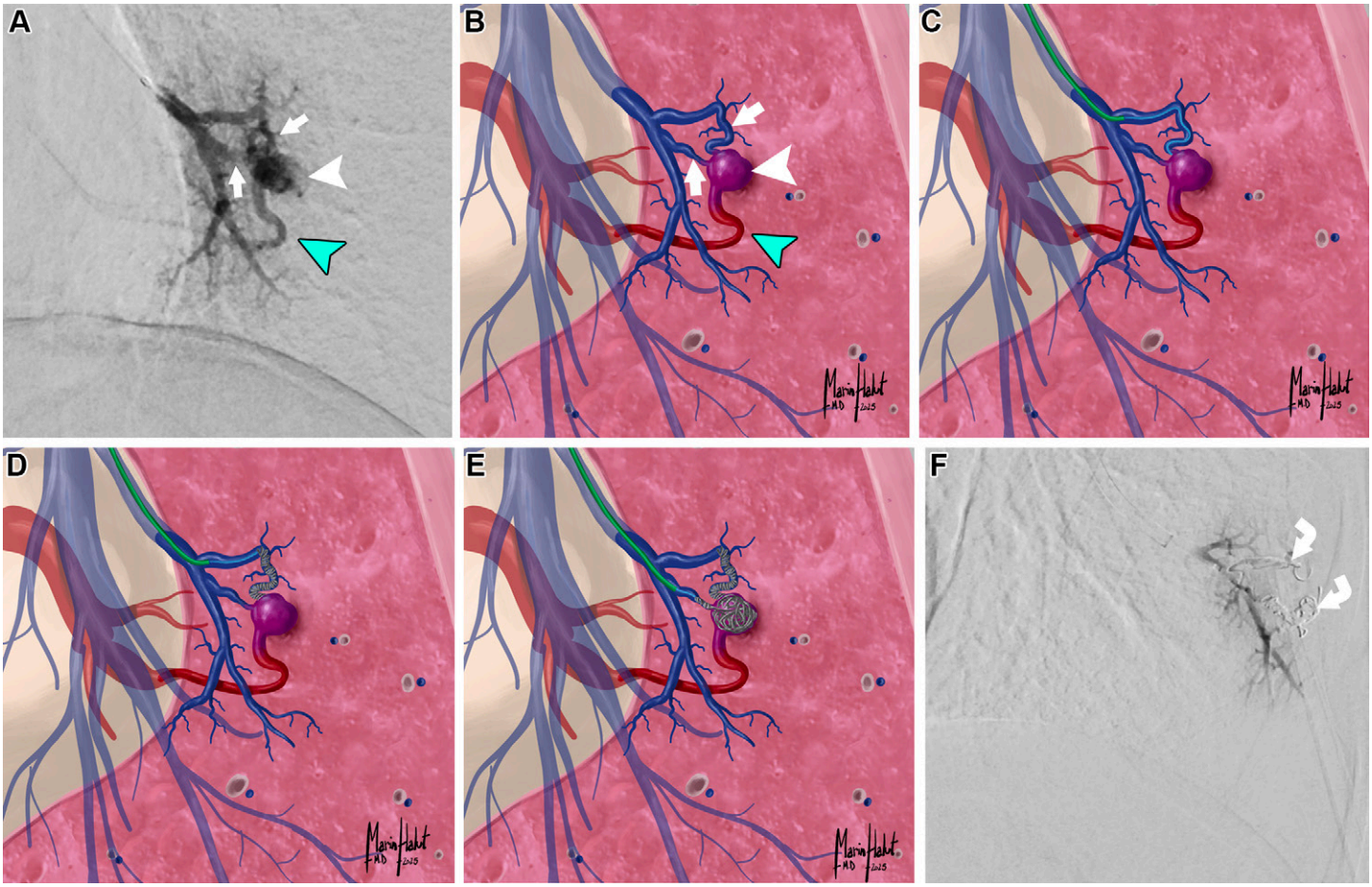


Figure 14. PAVM in a 55-year-old woman with suspected HHT without clinical symptoms. **(A)** DSA image shows a small complex PAVM in the left lower lobe, with two arterial feeders (arrows in **A** and **B**), an aneurysmal sac (white arrowhead in **A** and **B**), and a single draining vein (blue arrowhead in **A** and **B**). **(B)** Illustration based on the previous angiogram depicts the PAVM architecture. **(C)** A 4F catheter (green) is positioned at the ostium of the first feeder, while a microcatheter (blue) is advanced as distally as possible within the arterial feeder. **(D)** The first feeder is embolized through the microcatheter using detachable coils. **(E)** The aneurysmal sac and the second feeder are subsequently embolized with detachable coils. **(F)** The final DSA image confirms complete PAVM embolization with coils (arrows).

Complex PAVM Embolization

The treatment of complex PAVMs is more challenging due to the presence of multiple arterial feeders, some of which are small and tortuous. Each arterial feeder must be individually addressed based on its size, as is done in a simple PAVM embolization. Complete complex PAVM embolization often requires a combination of plugs and coils (20,23,47). In cases where all arterial feeders are small and tortuous, 0.018-inch coils may be the only viable option for embolization, as shown in Figure 14 and Movie 6. The PAVM persistence rate after embolization is higher in complex PAVMs than that in simple PAVMs (20).

Diffuse PAVM Embolization

Diffuse PAVMs are rare and extremely challenging to treat. Patients with diffuse PAVMs often present with hypoxemia and have a higher prevalence of neurologic complications, brain abscess, and hemoptysis, particularly in cases with bilateral involvement (16,59). The current interventional approach involves embolization of the numerous small arterial feeders as distally as possible, although this may not always be feasible due to the small size of the feeders. Occlusion devices include plugs or densely packed coils, depending on the feeder sizes (Fig 15; Movie 7). Given the large number of feeders that require treatment, the procedure is often staged over multiple sessions. Proximal occlusion should be avoided because systemic collaterals can reperfuse the PAVM (16), increasing the risk of late hemorrhagic complications due to the high pressure of systemic collateral flow. Despite embolization, hypoxemia may persist due to residual microfistulae (60).

Symptom recurrence is common in diffuse PAVMs after embolization with ongoing risks of complications. Recent case series have demonstrated excellent outcomes with surgical resection, including lobectomy, segmentectomy, and pneumonectomy, in adults and children with diffuse PAVMs (61). Surgery should be considered in patients with recurrence after embolization or with highly complex diffuse PAVMs, particularly in children, to minimize repeated sessions that lead to high radiation exposure. Diffuse symptomatic PAVMs require evaluation by a multidisciplinary HHT team, including interventionalists, surgeons, pulmonologists, and geneticists. In cases of extensive diffuse PAVMs, lung transplant may be considered (62). Medical therapies, including bevacizumab, thalidomide, and pomalidomide, have been used to manage

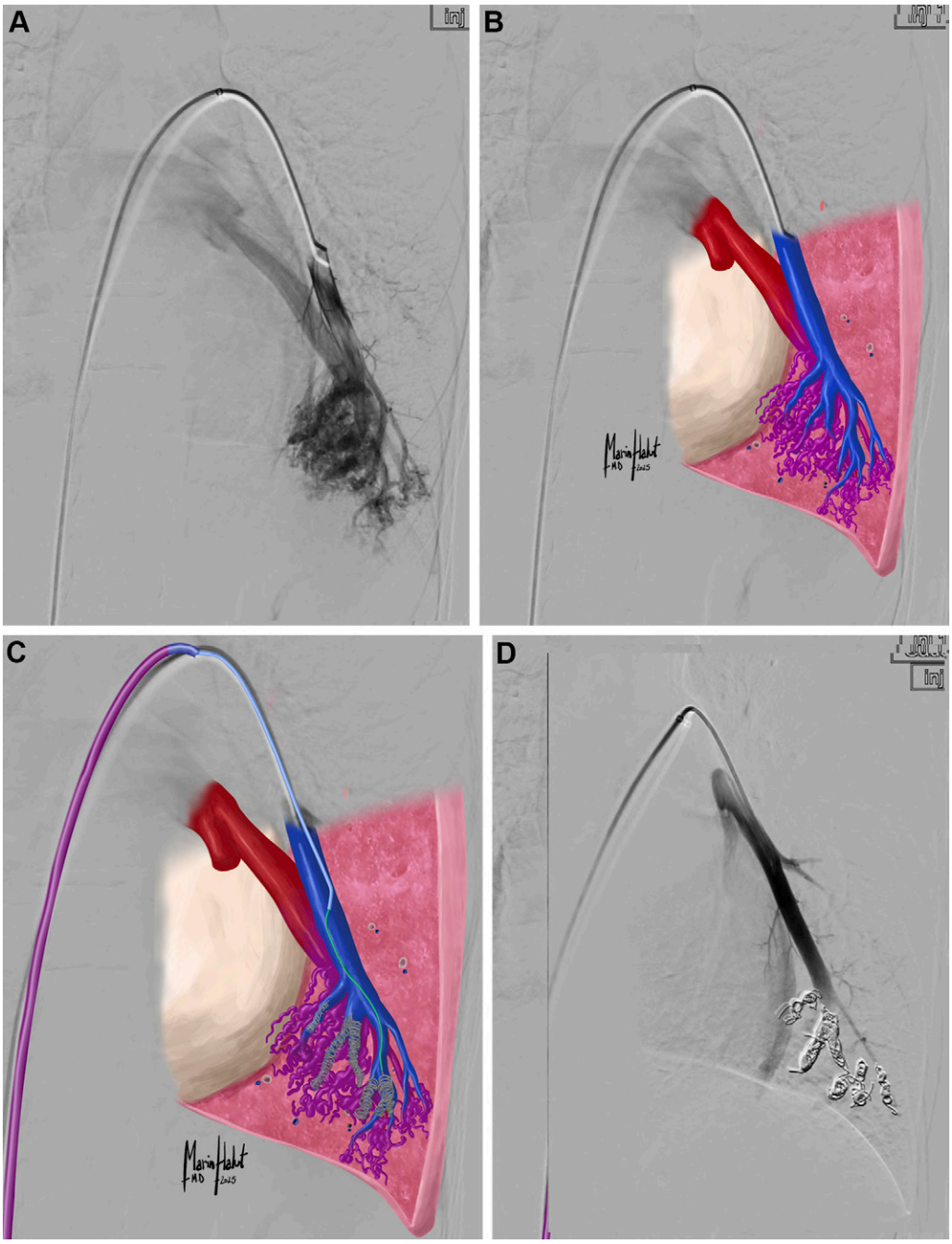


Figure 15. PAVM in a 18-year-old man with hypoxemia and clubbing. **(A)** DSA image shows a diffuse PAVM with multiple arterial feeders, innumerable microfistulae, and multiple draining veins. **(B)** Illustration based on the previous angiogram shows a diffuse PAVM with multiple arterial feeders, innumerable microfistulae, and multiple draining veins. **(C)** Illustration shows distal embolization of the arterial feeders with detachable coils through a microcatheter. **(D)** DSA image shows complete embolization of the PAVM.

epistaxis, reduce transfusion needs, and lower high cardiac output associated with liver arteriovenous malformations in patients with HHT (63). However, to our knowledge, none of these drugs have been explicitly used to target PAVMs.

Complications after PAVM Embolization

The most common immediate complication is pleurisy, which occurs in 6% of cases (64). Pleurisy is typically associated with small pulmonary infarctions and is usually self limiting (65). Clinically, patients may experience pain and dyspnea, which are generally well controlled with nonsteroidal anti-inflammatory drugs and analgesics. Symptoms often resolve spontaneously within 7–10 days. In rare cases, vessel perforation or aneurysmal sac rupture may occur due to catheter or guidewire trauma. This may result in minor hemoptysis from small vessel injury or, in more severe cases, hemothorax due to aneurysmal rupture. Intensive care unit support may be required for hemodynamic stabilization, and complete occlusion of the PAVM or injured vessel is essential to control bleeding.

The most serious complication is paradoxical embolism, which can arise from air, thrombus, or device migration. This may lead to stroke, transient ischemic attack, or infarction of other organs such as the liver or kidneys. Shovlin et al (62) reported a 1% rate of major complications, including death, periprocedural stroke, and hemopericardium (66). However, Shahin et al (64) found no major complications in their study of 4047 PAVM embolization procedures performed in 1865

patients (64). Chest pain and bradycardia, sometimes accompanied by transient electrocardiographic changes, have also been reported due to small air bubbles entering the coronary arteries (67). Other potential complications include bleeding at the access site, heart valve injury from catheter manipulation, and arrhythmias. Delayed complications, such as embolization device infections (Fig S2), are exceedingly rare (68).

The choice of imaging modality to evaluate complications depends on the type of complication. Pleurisy typically does not require imaging. However, chest radiography may be useful to assess for pleural effusion. Postprocedural hemoptysis can be evaluated using non–contrast-enhanced chest CT or CT pulmonary angiography to identify the source of bleeding. In cases of a stroke during the procedure, an initial non–contrast-enhanced brain CT followed by CT angiography is recommended to detect intravascular thrombus, embolic devices, or air embolism. If paradoxical emboli to other body regions are suspected, a contrast-enhanced CT targeted to the affected area is usually indicated. Iatrogenic paradoxical emboli may appear as a high-attenuation embolic device within the arteries or organs and may be associated with secondary infarction. In some cases, these emboli manifest with delayed symptoms or are discovered incidentally years after the procedure (Fig S3).

Outcomes and Follow-Up

The outcomes of PAVM embolization, excluding diffuse PAVMs, are generally excellent, as demonstrated in a recent meta-analysis. The treatment success rate of embolization using plugs and/or coils ranges from 86% to 98%, with an immediate technical success rate of 99% (64).

According to international recommendations, patients should be followed up after PAVM embolization using non–contrast-enhanced chest CT or CT pulmonary angiography. The first follow-up scan is typically performed 6–12 months after embolization, with subsequent scans conducted every 3 years to detect persistent or newly developed PAVMs (30). Patients with small untreated PAVMs or suspected PAVMs identified at TTCE but not visualized at CT should undergo follow-up chest CT every 1–5 years, depending on individual risk factors (30). While TTCE plays a limited role in follow-up, recent evidence suggests that low-grade right-to-left shunts detected at TTCE after embolization may not require further intervention, and follow-up chest CT can be safely omitted in these cases (69). Contrast-enhanced MRA also has limited utility at follow-up due to its relatively low spatial resolution, which may prevent the detection of newly developed PAVMs smaller than 5 mm. However, MRA can be useful after complex embolization procedures with a high coil burden, as it may help identify reperfusion through the coil mass (34).

At chest CT, assessment of postembolization PAVM persistence relies on contrast enhancement of the PAVM aneurysmal sac at CT pulmonary angiography or an aneurysmal sac diameter reduction of less than 70% detected at non–contrast-enhanced CT, observed 6 months after embolization (26,45). Non–contrast-enhanced CT can be performed using a low-dose radiation protocol in young patients. While contrast-enhanced CT offers superior diagnostic performance over non–contrast-enhanced CT, it carries a risk of paradoxical gas embolization during contrast agent injection due to persistent residual microshunting after embolization (30,70). Due to this persistent microshunting, lifelong use of intravenous-line filters for venous access and antibiotic prophylaxis during nonsterile dental or medical procedures is recommended. Additionally, scuba diving should be permanently avoided (30).

Persistent PAVMs

Persistent PAVMs after embolization can occur through four mechanisms, as shown in Figure 16 (24,48,71). In all cases, except for reperfusion through the accessory arteries, PAVM persistence is more likely to occur when the PAVM feeder is embolized too far from the aneurysmal sac (48,55).

Recanalization

Recanalization, defined as flow through the previously placed embolic material (Fig 16A), is the leading cause of persistent PAVMs, accounting for 68%–98% of cases (10,24,72). It primarily results from coil elongation, inadequate thrombosis, and fibrinolytic activity of the pulmonary arteries (72). Contributing factors include coil placement too far from the aneurysmal sac, insufficient packing or coil oversizing, a large feeding artery (20,67), and tobacco use (26).

Retreatment consists of crossing the recanalized coils to embolize the aneurysmal sac (Fig 17). This technique has been shown to reduce the persistence rates after re-embolization (71). If this approach is not feasible, the recanalized feeding artery is re-embolized proximally or, ideally, within the coil nest.

Reperfusion through Accessory Artery

Reperfusions in complex PAVMs can occur when a feeding artery is overlooked during the initial treatment or too small to be embolized at the time, later enlarging over time (Fig 16B). Retreatment involves embolization of the remaining feeding artery (71).

Reperfusion via Pulmonary-to-Pulmonary Collaterals

Reperfusion occurs when blood flows from adjacent pulmonary artery collaterals, with reversal of circulation in branches of the PAVM feeder beyond the embolization device (Fig 16C). This reversal circulation occurs through the capillary bed (71). PAVM re-embolization through pulmonary collaterals is generally not feasible because the caliber of the capillaries is too small. These reperfusions are among the most challenging to treat and may require retrograde pulmonary venous access, which is typically achieved with a transseptal approach to embolize the draining pulmonary vein, as seen in Figure S4 (73). This technique involves creating transseptal access to the left atrium by perforating the interatrial septum, typically with transesophageal or intracardiac echocardiographic guidance. Access is achieved via the femoral vein using a specialized needle or a radiofrequency-assisted system (73). Once access is established, embolization can be performed in a manner similar to the antegrade approach by targeting the aneurysmal sac.

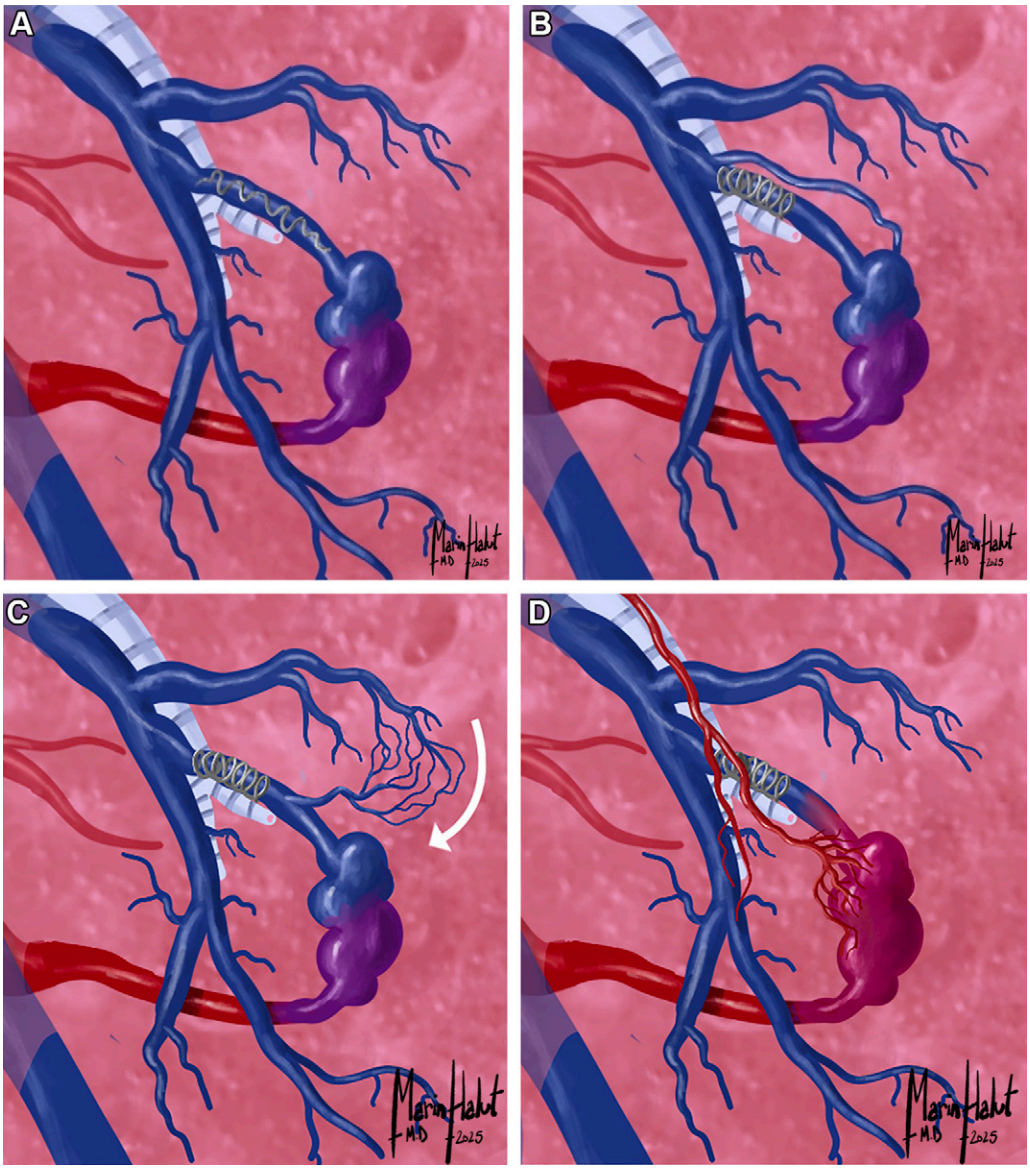


Figure 16. Illustrations depict the four mechanisms that cause PAVM persistence. **(A)** Recanalization through embolic material, as illustrated with an elongated coil. **(B)** Reperfusion of the PAVM through an accessory PAVM feeding pulmonary artery. **(C)** Reperfusion of a pulmonary artery collateral through reversed circulation (arrow) in the capillary bed and in a branch of the PAVM feeder beyond the occlusion. **(D)** Reperfusion through a systemic artery, as illustrated with a bronchial artery.

Systemic-to-Pulmonary Reperfusion

Systemic feeders typically originate from bronchial (Fig 16D), internal mammary, intercostal, or subclavian artery collaterals. While these reperfusions create a left-to-left shunt without the risk of paradoxical embolization, they significantly increase the risk of hemoptysis due to elevated systemic pressure in fragile collaterals and thin-walled aneurysmal sac. Retreatment consists of embolization of the systemic collaterals. Due to vessel tortuosity, distal embolization with coils can be challenging, as seen in Figure S5, while the use of particles or liquid embolic agents carries a risk of paradoxical embolization (18). In case of embolization failure in symptomatic patients, segmental resection may be necessary, whereas asymptomatic patients can be monitored (10).

Pregnancy and PAVM

The risk of PAVM-related complications increases during pregnancy, necessitating management in a multidisciplinary setting at a tertiary care center (6). This risk is particularly elevated in the 2nd and 3rd trimesters due to physiologic changes, with decreased peripheral resistance and increased cardiac output of nearly 50% that may exacerbate existing PAVMs (74). Case series of pregnant women with HHT and untreated PAVMs have reported a high complication rate (13%), including transient ischemic attack, hemothorax, and myocardial infarction (75). The maternal mortality rate associated with PAVMs during pregnancy is estimated at 1% (1). Given these risks, women with HHT who are considering pregnancy should undergo screening with TTCE and/or CT and any identified PAVMs should be treated before pregnancy (9).

In asymptomatic pregnant women with HHT who have not been previously screened for PAVMs, TTCE, or low-dose non–contrast-enhanced chest CT is recommended, with chest CT ideally performed in the early 2nd trimester. Interventions should generally be deferred until the second trimester unless urgent clinical indications necessitate earlier treatment (6).

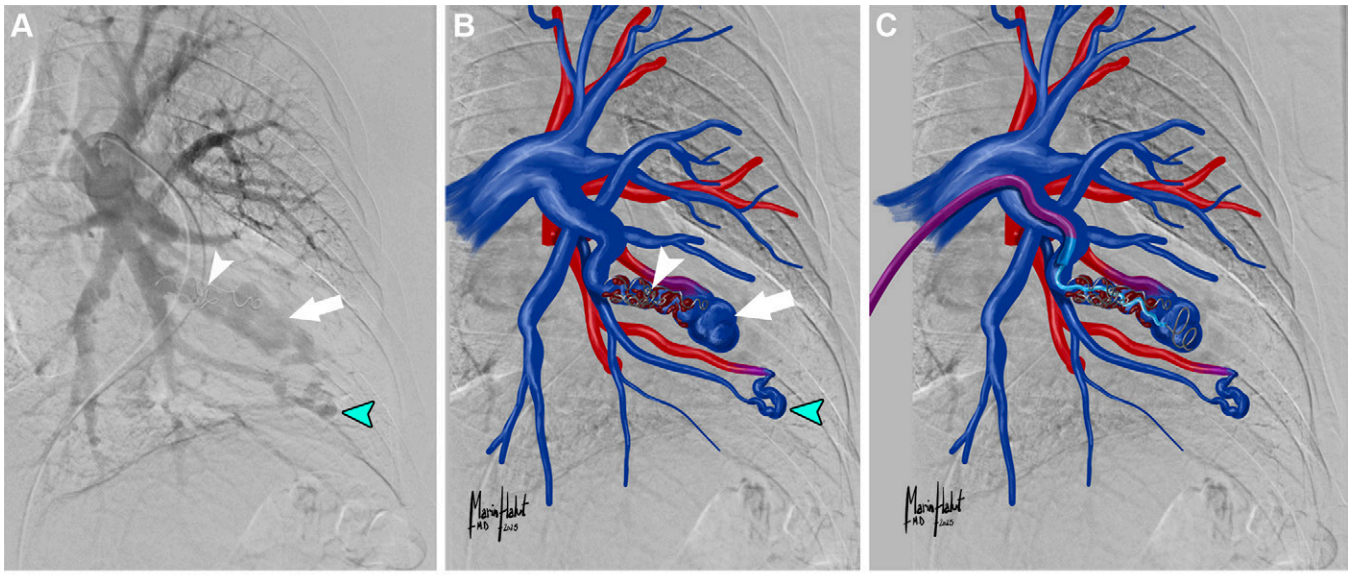


Figure 17. Persistent PAVM in a 62-year-old man with HHT, epistaxis, and intermittent gastrointestinal bleeding. **(A)** DSA image shows a recanalized PAVM in the left lower lobe, with opacification of the aneurysmal sac (arrow in **A** and **B**) and distal arterial feeders (white arrowhead in **A** and **B**) despite prior coil embolization, where the coils appear elongated. Another simple PAVM is also visible in the lower lobe (blue arrowhead in **A** and **B**). **(B)** Illustration based on the previous angiogram depicts the angioarchitecture. **(C)** Illustration shows the distal feeder and previous coil nest being crossed with a microcatheter, allowing direct embolization of the aneurysmal sac with coils. **(D)** Nonsubtracted angiogram confirms complete embolization of the aneurysmal sac with coils.

Conclusion

Embolization is a safe and effective treatment of PAVMs and has high technical success rates and excellent clinical outcomes. By preventing life-threatening complications such as stroke and brain abscess, PAVM embolization plays a critical role in reducing morbidity and mortality, particularly in patients with HHT. When performed rigorously with proper techniques, procedural complications are rare. Although the treatment of complex PAVMs is more challenging, it significantly lowers the risk of PAVM-related complications. However, these lesions have a notable rate of postembolization persistence. Therefore, long-term follow-up is essential to identify and manage persistent PAVMs, ensuring optimal patient outcomes.

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