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Pulmonary Angiography

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Angiographic opacification of the main and branch pulmonary arteries is an infrequent but important procedure in the cardiac catheterization laboratory. The procedure was first reported by Robb and Steinberg in 1938 (1). Though the basic objective is unchanged, virtually unlimited catheter designs are available, iodinated contrast safety has increased by generations, and radiographic images can resolve seventh-order pulmonary arteries. Alternative technologies for capturing an angiographic image have also evolved, including computed tomography (CT), and magnetic resonance (MR) imaging. With the use of CT and MR angiography in the workup of suspected pulmonary embolism, fewer diagnostic pulmonary angiograms are being performed, but increasingly, more therapeutic options are catheter directed (2). Maintenance of technical skills in pulmonary arterial catheterization is therefore vital. The principles of pulmonary angiography should be part of the basic knowledge of all physicians performing catheterizations.

THE CHANGING ROLE OF CATHETER PULMONARY ANGIOGRAPHY

Indications

The basic indications for pulmonary angiography are summarized in the guidelines developed by the American College of Radiology and the Society of Cardiovascular and Interventional Radiology (3). The most common indication for pulmonary angiography probably remains pulmonary embolism. The patient may arrive for pulmonary angiography from the emergency room, after scintigraphy, or after CT or MR angiography. It is important for the conventional angiographer to understand the limitations of each imaging technique (CT and MR), to tailor the catheter angiographic study to achieve a diagnosis expeditiously and with the least risk to the patient.

CT and MR Pulmonary Angiographic Limitations

Reduced image acquisition time for both CT and MR scanners has allowed images of the pulmonary arteries to be obtained during a single breath-hold while maintaining resolution. CT images can be obtained fast enough to eliminate significant image degradation from adjacent cardiac motion, and MR images can be sampled from the same phase in the cardiac cycle to freeze heart and vessel motion. Peripheral intravenous injection of iodinated (CT) or chelated gadolinium (MR) contrast material increases contrast between flowing blood and stationary tissue, producing an angiographic effect. With both modalities, cross-sectional or reconstructed three-dimensional images can be manipulated on monitors to detect subtle nonocclusive emboli.

Contrast-enhanced helical CT of the pulmonary arteries has been reported to have 90% sensitivity and 96% specificity for detection of emboli within the central pulmonary arteries (4). When Goodman et al. included subsegmental vessels, sensitivity and specificity dropped to 63% and 89%, respectively (5). Drucker and colleagues had similar findings, including subsegmental vessels, with a sensitivity of 60% and specificity of 81% (6). The CT scanners in these studies probably excluded most subsegmental vessels, as only 15 cm of the chest were scanned, starting at the top of the aortic arch. With multi-row detector CT equipment today, thin sections of the whole lung can be obtained in a single breath-hold, but subsegmental emboli may not be visualized because of limitations of spatial resolution. Partial volume effects lower contrast resolution in the right middle lobe and lingular vessels.
From a clinical perspective, failure to detect subsegmental emboli may be a major limitation of CT. For example, using the PIOPED data, Stein et al. found that 6% of patients with pulmonary embolism had emboli limited to the subsegmental vessels (7). In the subgroup of patients with low-probability perfusion scans and no cardiopulmonary disease, patients with emboli limited to subsegmental vessels increased to 30%. In a retrospective review of patients with pulmonary embolism, Oser et al. found 30% of emboli limited to subsegmental vessels in 88 patients with positive pulmonary angiogram (8). Two patients had segmental emboli limited to the lingular or right middle lobe vessels. Although these peripheral emboli in themselves may not be immediately life-threatening, failure to detect them may lead to failure to treat the underlying condition and thus expose the patient to the risk of recurrent and potentially fatal emboli.

MR pulmonary angiography is at an earlier stage of development than CT angiography. Pulmonary MR vascular imaging is difficult because of artifacts created by motion and the air–vessel interface. Results of recent clinical studies are encouraging. Meaney et al. found sensitivities of 100%, 87%, and 75% in three independent readers of scans for suspected pulmonary embolism (9). As the technical limitations of MR pulmonary angiography are overcome, the technique may rival or surpass CT as the preferred noninvasive pulmonary angiographic technique.

### Implication for Catheter Angiography After Cross-sectional Imaging

Because of the limited ability of CT and MR angiography in detecting subsegmental emboli, the patient presenting for diagnostic pulmonary angiography after a negative or nondiagnostic CT or MR study will require meticulous examination of the subsegmental vessels. Superselective injections with or without magnification may be indicated. Another reason to prefer superselective angiography is that iodinated contrast will have been given in CT, which will reduce the acceptable contrast dose available for same-day diagnostic or therapeutic pulmonary angiography.

### TECHNICAL REQUIREMENTS

#### Digital Versus Cut-Film Angiography

For diagnostic pulmonary angiography, the American College of Radiology recommends at least a high-resolution image intensifier and television chain, plus a standard 14-inch serial film changer (3). Conventional film (with two views of each lung) is the only imaging modality that has been validated against clinical outcome (in pulmonary embolism) in a large trial (10). Recently, Hagspiel et al. found digital pulmonary angiography with selective pulmonary arterial injections equivalent to conventional cut-film angiography in diagnostic performance and image quality in the diagnosis of pulmonary embolism (11). In a prospective trial in 80 patients, Johnson et al. found digital subtraction pulmonary angiography allowed more confident detection of pulmonary emboli than did conventional cut film, without loss of accuracy (12). Though not included in the statistical analysis, Johnson et al. found more emboli with digital subtraction than cut film and with better interobserver agreement. Forauer and colleagues followed 54 patients for a mean of 12.1 months after a negative digital study for pulmonary embolism and found no documented pulmonary embolism (13). Other advantages of digital pulmonary angiography over cut film include rapid image acquisition and flexible display format. Images can be viewed individually or in cine format on the monitor, subtracted or unsubtracted. Masks can be selected image by image and pixels shifted to best match the anatomy. For these reasons, digital pulmonary angiography with selective intraarterial contrast injections has virtually replaced cut film studies.

One area in which digital angiography remains inferior to cut film is image resolution. For 1,024×1,024 matrix images laser printed on film, resolution is 1.6 line pairs per millimeter (lp/mm) for a 25-cm image intensifier, and 1.2 lp/mm for a 38-cm image intensifier. Conventional film resolves from 4 to 7 lp/mm. Resolution on film recorded in a cine camera with a 25-cm image intensifier is 2.1 lp/mm (14).

#### Radiation Dose Considerations

The dose per image for digital, cut-film, and cine angiography is similar (with digital images probably slightly higher). The higher total dose for cineangiography results from the speed of serial acquisition, since the exposures
occur at 30 to 60 images per second. Digital systems are now capable of running 15 images per second in a 1,024 matrix and up to 30 frames per second in a 512 matrix, at a cost of higher patient radiation dose.

The FDA has addressed x-ray-induced skin injuries due to long fluoroscopically guided procedures (15). Although it is unlikely that diagnostic pulmonary angiography would result in radiation injury, the laboratory director should ensure that the equipment operates within NCRP guidelines (16) and that its operators are well trained in its use. A medical physicist should supervise the equipment and quality improvement program. Most angiographic systems now produce a dose estimate for the patient, including both fluoroscopic times and angiographic run dose. This should be included as part of the patient's medical record. Pulsed fluoroscopy modes can reduce fluoroscopic dose. Whenever possible these should be used for the benefit of both patient and operator.

Monitoring Equipment and Personnel

Safe pulmonary arteriography requires patient monitoring equipment for continuous heart rate, cardiac rhythm, and blood pressure along with personnel skilled in its use. Virtually all patients should be placed on supplemental oxygen. A pulse oximeter or end-tidal carbon dioxide monitor should also be used. The radiologic technologists in the room should be completely familiar with all x-ray and angiographic equipment, including injectors, catheters, guidewires, and patient monitors. Certification as a vascular and interventional radiologic technologist ensures appropriate training. A qualified nurse should monitor the patient and record vital signs. The technologists should be trained in basic cardiac life support, and the physicians and nurses participating in the procedure should be trained in advanced cardiac life support. For pulmonary angiography, a crash cart should be located within the immediate area. Medical or surgical support teams, though only rarely required, must be promptly available in the event of complications.

All angiography procedures must be part of a laboratory's ongoing quality improvement monitoring process. Periodic review of indications, outcomes, and complications provides the opportunity to improve patient care.

CONTRAINDICATIONS

There are no absolute contraindications to pulmonary angiography. Individuals with left bundle branch block are at risk for developing complete heart block during right heart catheterization due to minor trauma of the right side of the ventricular septum. Nevertheless, passage of the catheter into the pulmonary artery for angiography can be performed safely as long as individuals skilled at transvenous pacing and the necessary equipment are immediately at hand.

Pulmonary hypertension has been considered a relative contraindication to pulmonary angiography. With the use of nonionic, low-osmolar contrast, and prophylactic oxygen, the risk of complications may be reduced. Pitton et al. measured hemodynamic parameters in patients with normal pulmonary pressure, moderate pulmonary hypertension, and severe pulmonary hypertension during pulmonary angiography with multiple selective injections of iopamidol (contrast total 167.9 ± 34.2 mL), a nonionic, low-osmolar iodinated contrast agent (17). All patients were on oxygen. Even in the patients with severe pulmonary hypertension (systolic pulmonary artery pressure more than 60 mm Hg), bolus injection of nonionic contrast into the pulmonary arteries caused no major hemodynamic effects in patients given supplemental oxygen (17).

In patients with a history of anaphylactoid reaction to intravenous contrast, the risk of a reaction can be reduced with use of preprocedural corticosteroids (orally if time permits or intravenously in emergent studies), and with use of nonionic low-osmolar contrast media. In patients with a history of allergy (food allergy or asthma), nonionic contrast should be used.

A number of cases of acute fatality after pulmonary angiography in patients on amiodarone have been reported. For example, Malden et al. describe a case of acute pulmonary toxicity and death after pulmonary angiography despite the use of nonionic contrast material (18). Caution must be used when considering pulmonary angiography in a patient on amiodarone.

COMPLICATIONS
Although pulmonary angiography is the definitive diagnostic test for imaging the pulmonary arteries, it is an invasive procedure that is accompanied by some risk of complication. Major complications can be defined as those that are life-threatening and do not respond promptly to therapy or that require intensive-care monitoring or prolonged hospitalization (e.g., when cardiopulmonary resuscitation, endotracheal intubation, dialysis, or blood transfusion is required). Minor complications can be defined as those that regress spontaneously without long-term morbidity, even if patients require prolonged monitoring. The complications seen during the PIOPED study (10) were tabulated according to these definitions (Tables 13.2 and 13.3). Of note, the study involved injecting high-osmolar ionic contrast through pigtail catheters with images recorded on conventional film.

At least three of the deaths reported by Stein and colleagues may have been due to severe baseline cardiopulmonary compromise rather than to catheterization or angiography (10). Mills and coworkers report three deaths in patients with right ventricular end-diastolic pressure of more than 20 mm Hg and conclude elevated right ventricular filling pressures are associated with increased complications from pulmonary angiography (19). Marsh et al. reported the death of a patient with severe pulmonary hypertension after hand injection of only 10 mL of contrast material into the main pulmonary artery (20).

Unlike previous large series, no myocardial perforations occurred in the PIOPED series, attributed to the exclusive use of pigtail type rather than to straight catheters, such as the Eppendorf. Renal failure and insufficiency occurred in the PIOPED group in 0.3% and 1.0%, respectively, more often in elderly patients. This complication was not evaluated in the Mills study, but Stein and coworkers found the volume of contrast injected was not significantly greater in those patients having renal complications.

PROCEDURE

Venous Access

The right common femoral vein is the preferred venous access site, as it provides a relatively straight course to the inferior vena cava and right heart. This site also facilitates insertion of an inferior vena cava filter if indicated, to prevent recurrent thromboemboli in patients who are at high risk for anticoagulation (21). If iliac vein or caval thrombosis is present, the right internal jugular vein also provides excellent anatomy for accessing the pulmonary arteries or inferior vena cava. The left internal jugular vein is preferable if only angiography is required, as catheters preferentially seem to follow the circular path from access to right pulmonary artery (22). If access here is precluded, then the left femoral vein, followed by the right or left basilic vein at the antecubital fossa, can provide adequate access.

Patients who come to pulmonary angiography are frequently anticoagulated, and those in whom pulmonary embolism is found may be candidates for thrombolytic therapy. This places such patients at higher risk for hemorrhagic complications at the puncture site. A single-wall puncture technique is preferred to avoid inadvertent through-and-through puncture of the femoral artery (see also Chapter 4). Because of compression of the vein on entry, the needle may also puncture the back wall of the vein, with blood flow seen only during slow withdrawal of the needle. Once venous blood return is obtained, the position of the needle is fixed and a guidewire is introduced. Any floppy-tip, straight, or J wire can be used.

Pulmonary Catheterization

After appropriate dilation of the entry site, a 6F to 7F pulmonary catheter is placed over the wire. Catheters of this size are necessary to provide a lumen that will accommodate flow rates of 20 to 25 mL/sec. A 4F nylon pulmonary catheter has recently been reported that will allow flow rates of 20 mL/sec at 1,050 psi (23). Using a 4F catheter may reduce access site complications and, when used from a basilic vein (as it is designed for), removes the need for bedrest. A sidearm sheath can be left in place after the study if the patient is to go on to thrombolytic therapy. Recognizing that there are many techniques for selectively catheterizing the right and left pulmonary arteries, we describe three common approaches in Fig. 13.1.
Techniques for pulmonary artery catheterization. (A) Straight body pigtail catheter and tip deflecting wire. (1) The pigtail catheter is placed in the right atrium. (2) The wire is deflected to point toward the right ventricle. (3) The wire is fixed, and the catheter is advanced over it into the right ventricle. (4) The tip deflection is released. (5) Counterclockwise rotation of the catheter swings the pigtail anteriorly. Simultaneous advancement of the catheter places it into the main pulmonary artery. Advancing the catheter further usually takes it into the left main pulmonary artery. The tip-deflecting wire is utilized to direct the catheter downward and to the right for right main pulmonary artery catheterization. (B) Angled pigtail catheter. (1) The pigtail catheter is placed in the right atrium. (2) Advancing the catheter places the tip in the right ventricle. (3) Clockwise rotation, with simultaneous advancement places the tip in the main pulmonary artery. (C) Balloon catheter. The balloon is inflated under fluoroscopic guidance in the common iliac vein. It is advanced under observation through the right heart and into the main pulmonary artery. Selection of right and left pulmonary arteries is assisted with conventional or tip-deflecting wires. If a pigtail catheter is needed after use of a balloon catheter, 260-cm Rosen wire is used for the exchange.

The presence of a properly placed inferior vena caval filter does not necessarily preclude a transfemoral approach. Safe transfemal angiography has been reported with straight, 3-mm J, and 15-mm J wires through stainless steel Greenfield (Meditech/Boston Scientific, Watertown, MA), Vena-Tech (B. Braun Medical, ), and bird's nest (Cook, Bloomington, IN) filters (24). It is important to insert and withdraw catheters only while they are straightened over a wire, to minimize the likelihood of hooking the filter. During interventional procedures that involve multiple catheter exchanges, a long sheath may be placed with its leading tip beyond the filter.

Catheter Selection

Although many catheters are available for pulmonary arteriography, virtually all are variations of two basic designs. The pigtail-type catheter confers safe passage through the right heart. There have been no reports of right ventricular perforation with a pigtail catheter (22). Various curve configurations facilitate catheterization of the pulmonary artery and the subselection of pulmonary artery branches by active catheter manipulation. The pulmonary pigtail should be tight (<1 cm), permitting use of the same catheter for subselective injections (22). In contrast, balloon-tipped catheters are passively carried by blood flow through the right heart chambers and into the pulmonary arteries. Side-holes in the catheter shaft then allow power injection in the main branches, while an end-hole makes balloon occlusion angiography possible with the same catheter (Fig. 13.2). All pigtail catheters must be removed from the pulmonary arteries straightened by a floppy-tip guidewire under fluoroscopic observation, since the catheter tip may hook a papillary muscle, chordae tendineae, or tricuspid valve leaflet during withdrawal. Balloon catheters are first deflated and can then be removed without fluoroscopy.

FIG. 13.2.

Catheters for pulmonary angiography. Left to right: the Nyman, Grollman, and straight pigtail catheters, and the balloon occlusion catheter with side-holes distal to the balloon (Berman type).

Hemodynamic Assessment

Hemodynamic assessment should precede pulmonary angiography, allowing rational selection of appropriate supportive, therapeutic, and prophylactic measures. For example, if prompt correction of circulatory inadequacy cannot be achieved in a patient with pulmonary thromboembolism, definitive therapeutic measures to remove pulmonary emboli can be undertaken. Examination of the right heart pressures may reveal unsuspected alternative diagnoses, such as cardiac tamponade, or left ventricular failure. All right heart and pulmonary pressures need to be obtained before injection of contrast. Damping of the pressure in the main pulmonary artery may indicate massive embolism, with the catheter holes embedded in the embolus. Some clinical situations will require that a pulmonary wedge pressure be obtained. A balloon flotation catheter can be used to gain access to the pulmonary circulation for wedge pressure measurement, with subsequent exchange for a pigtail angiographic catheter.

Contrast Media
In most medical centers, low-osmolar iodinated contrast is preferentially used for pulmonary angiography, recognizing that this practice has not been shown to produce a significant reduction in mortality from contrast reaction. Moreover, changes in pulmonary hemodynamics are not significantly different when high-osmolar or low-osmolar agents are used (25). A reduction in coughing and other forms of involuntary motion with low-osmolar agents (25), however, allows the relatively motion-free images that are essential to high-quality pulmonary angiography.

Additional precautions should be taken when using low-osmolar contrast material to prevent thrombotic and embolic complications. In vitro activation of platelets has been demonstrated with iohexol and iopamidol in a limited number of volunteers (26). Increased plasma levels of plasminogen activator type 1 were found in patients after pulmonary angiography with iohexol, and increased thrombin–antithrombin III complexes were found after iohexol and ioxaglate (27). Prolonged contact of contrast with blood should be avoided. Some institutions utilize ionic contrast for preliminary hand injections, since ionic contrast inhibits coagulation, reserving low-osmolar agents for power injection; other institutions add heparin to low-osmolar contrast.

FIG. 13.3.

Iodinated contrast dependency (gravitational layering). Single lateral view from a left pulmonary angiogram obtained with the patient supine demonstrates poor opacification of all the anterior pulmonary arteries (arrows).

The amount of contrast utilized is determined by the size of and flow in the vessel selected, assessed during a test hand injection. The right and left main pulmonary arteries usually require 40 to 50 mL of contrast at 20 to 25 mL/sec. For digital recording techniques, a total of 25 mL is usually sufficient. As smaller vessels are selected, the rate and volume are decreased. For balloon occlusion angiography of segmental vessels, a hand injection of 5 to 10 mL is used.

Since the density of contrast is greater than that of blood, gravity tends to cause preferential opacification of the dependent portions of the lung in the supine patient. Pulmonary arteries of the middle lobe, lingula, and anterior segments of the upper lobe may therefore not be satisfactorily opacified (Fig. 13.3).

Filming

Two views of each lung are performed in the frontal and 45° ipsilateral posterior oblique (i.e., 45° right posterior oblique for the right lung) for each lung. Although the lateral is the true orthogonal view to the frontal projection, it is not desirable for most cases of pulmonary angiography, since even selective right or left injections frequently cause reflux into the opposite lung that may confuse interpretation. Use of the frontal and 45° oblique view has been validated for pulmonary embolism in a large clinical trial (10).

Filming rates are based on the normal transit of contrast through the lung. Injected contrast reaches the capillaries in 2 to 3 seconds, and the left atrium fills in 4 to 6 seconds (28). Conventional x-ray filming rates are usually three images per second for 3 seconds and then one image per second for 6 seconds. With digital systems, a full second of masks is obtained before injection (about one cardiac cycle). For most indications, filming at six images per second is sufficient. Higher rates may be used in uncooperative patients or in situations where high flow is expected (e.g., in pulmonary arteriovenous malformations).

ANATOMY AND PHYSIOLOGY

Physiology

The pulmonary arterial system has low resistance and low pressure when compared with the systemic arterial system, with a normal main pulmonary artery pressure of 22/8 mm Hg (mean, 13 mm Hg). The main pulmonary artery is an elastic vessel (like the aorta), which serves as a reservoir for the right ventricular output. At the level of the bronchi–
bronchiolar junction, muscular arteries 1.0 to 0.1 mm in diameter have a well-developed medial smooth muscle layer. Below 0.1 mm, pulmonary arteries are essentially endothelial tubes leading into the capillary networks surrounding alveoli.

The pulmonary arterial system can accommodate large changes in volume, mostly by the recruitment of previously collapsed vessels rather than by distension of open vessels. Evidence of this is seen in postpneumonectomy patients, in whom the pulmonary vascular resistance typically remains normal despite the loss of half of the pulmonary vascular bed.

**Anatomy**

The main pulmonary artery arises from the pulmonary conus of the right ventricle, anterior and to the left of the aorta. It ascends 4 to 5 cm in a posteromedial direction until its bifurcation into the right and left pulmonary arteries. The right pulmonary artery has a mean diameter of 23.4 mm and courses horizontally in the mediastinum anterior to the right mainstem bronchus. The right upper lobe branch arises within the mediastinum before the right hilum. The left pulmonary artery mean diameter is 26.4 mm and is a direct posterior continuation of the main pulmonary artery, passing over the left mainstem bronchus to descend posterior to the bronchus before the origin of the left upper lobe branch. Thus the proximal portion of the left pulmonary artery is foreshortened in a frontal view and is best seen in a lateral or right posterior oblique view.

Within the lung, the vessels then branch in either a bifurcational (two branches of similar size), or collateral (one small branch at a 30° to 80° angle, with the larger branch of similar size as the parent) fashion (Fig. 13.4). Lobar and segmental branching is tremendously variable but related to bronchial branching. In addition, “supernumerary” branches outnumber conventional branches and penetrate the lung directly (29). The pulmonary arteries are fairly evenly distributed throughout the lung. The segmental pulmonary veins are variable. They form two superior and two inferior veins that enter the left atrium. The left veins may join to form a common vein within the pericardium (29). The anatomy of the pulmonary arteries is displayed in Fig. 13.5.

**FIG. 13.4.**

Pulmonary artery branching. (A) Bifurcational branching: Diameter of the daughter branches is similar and the sum of them equals or exceeds the parent. (B) Collateral or disproportionate branching. The diameter of the daughter branch is much less than the parent vessel. It is important not to interpret collateral branching configurations as abnormal.

**FIG. 13.5.**


**ANGIOGRAPHIC FINDINGS AND INTERPRETATION**

**Pulmonary Artery Stenosis**
An increasing number of patients with repaired congenital heart disease now survive into adulthood and may present with pulmonary vascular stenoses and occlusions. Most pulmonary arterial and venous stenoses occur in association with congenital cardiac disease such as tetralogy of Fallot, truncus arteriosus, pulmonary valvular stenosis, patent ductus arteriosus, aortic stenosis, and ventricular septal defects.

Congenital single or multiple stenoses may be present without cardiac anomalies (Fig. 13.6). Stenosis may also be secondary to rubella, chronic infections (such as histoplasmosis), or infestations (such as schistosomiasis). Stenoses are associated with idiopathic hypercalcemia. Isolated stenoses may present after pulmonary artery banding after systemic to pulmonary artery shunts such as Blalock-Taussig, Waterston-Cooley, or Glenn anastamoses. Lung transplant pulmonary arterial stenoses are not common and carry a poor prognosis (30).

FIG. 13.6.

Left interlobar pulmonary artery stenosis. Left pulmonary angiogram of isolated pulmonary arterial stenosis in an adolescent male.

It is important to measure the pressure gradient across the suspected stenosis, as the high flow in pulmonary arteries may create a significant pressure gradient despite the angiographic appearance of a mild stenosis (Fig. 13.7).

FIG. 13.7.

Transplant pulmonary arterial stenosis. Left anterior oblique view of a left pulmonary arteriogram in a patient 2 months after left lung transplantation. The stenosis (arrows) appears mild in this view, but a pressure gradient of 20 mm Hg was measured across the stenosis.

Angioplasty and stent placement for treatment of pulmonary artery stenoses have been used primarily for treatment of congenital stenoses (31). Only sporadic case reports of angioplasty or stent placement for acquired pulmonary stenoses are in the literature (32).

Pulmonary Arteriovenous Communications

Pulmonary arteriovenous malformation (PAVM) is thought to be due to an embryologic defect in the terminal capillary loop. Polycythemia and low arterial PO$_2$ are manifestations of the extracardiac right-to-left shunt. Most patients with PAVMs are asymptomatic, although dyspnea, cyanosis, digital clubbing, and hemoptysis may be present. Paradoxical emboli via PAVMs can result in cerebrovascular accident or abscess. PAVMs are classified into two types (33). Simple PAVMs are usually a complex branching mass, supplied by one to three subsegmental arteries, all arising from the same segmental artery. Complex PAVMs are supplied by two or more different segmental arteries. Complex PAVMs are more frequent in the right middle lobe or lingula.

The walls of PAVMs are quite thin. Multiple PAVMs are present in one-third of cases. From 40% to 65% of PAVMs are associated with hereditary hemorrhagic telangiectasia (Rendu-Osler-Weber syndrome). PAVMs are seen rarely with Fanconi's syndrome (pancytopenia, radial ray deformities, and brown skin pigmentation).

Screening for PAVMs can be done noninvasively with bubble echocardiography or spiral CT (Fig. 13.8). When intervention is planned, selective pulmonary angiography is necessary, with frontal and both oblique views of each lung. The entire lung volume needs to be filmed, as small, subpleural PAVMs may be present (33). When PAVMs are present in the lingula or right middle lobe, lateral views should also be obtained.

FIG. 13.8.

Pulmonary arteriovenous malformation. (A) Digital subtraction right interlobar pulmonary angiogram demonstrates
two feeding arteries, and (B) single draining vein in a 40-year-old dyspneic female. Shaded surface reconstructed display from her spiral CT without contrast (C) displays the architecture of the malformation well. (CT courtesy of G. Rubin, Stanford University Hospital, Stanford, CA.)

PAVMs can be percutaneously embolized with detachable balloons or coils (Fig. 13.9) (33). With the potential for direct systemic emboli, extreme caution must be exercised, and angiographic technique must be meticulous to avoid air embolism, catheter thrombosis and embolism, or systemic deployment of occlusion devices.

**FIG. 13.9.**

Pulmonary arteriovenous malformation with percutaneous embolization. A: Digital image displaying Amplatz spider vascular occlusion device (arrows) trailed by multiple coils in therapeutic embolization of the arteriovenous malformation seen in Figure 13.8. B: Right pulmonary angiogram confirms occlusion of the fistula.

Acquired pulmonary arteriovenous shunts can be secondary to trauma, infection, or hepatogenic angiodysplasia (34). Arteriovenous shunts seen in chronic infections of the lung may involve normal or anomalous feeding arteries and communicate with either pulmonary arteries or veins (29). Infection-related shunts are seen in bronchiectasis, invasive aspergillosis, tuberculosis, and schistosomiasis.

**Diffuse or Focal Attenuation of Pulmonary Vessels**

Angiography may be requested in cases of pulmonary hypertension of unknown etiology to exclude chronic pulmonary embolism. In primary pulmonary hypertension (Fig. 13.10), dilatation of the proximal pulmonary arteries is present, with smooth, rapid tapering of the vessels distally. A distal corkscrew appearance of the arteries may also be seen (29). Similar vascular findings are present in patients with secondary hypertension, but these patients will have an identifiable pulmonary, mediastinal, or cardiac cause of pulmonary hypertension.

**FIG. 13.10.**

Primary pulmonary hypertension. 45° right anterior oblique of the left pulmonary angiogram of a 30-year-old male with primary pulmonary hypertension. Note the rapid tapering of segmental vessels.

**FIG. 13.11.**

Primary evidence of acute pulmonary thromboembolism. Single image from a balloon occlusion right lower lobe pulmonary cineangiogram demonstrates multiple intraluminal radiolucencies, almost completely outlined by contrast as primary evidence for thromboemboli.

In pulmonary emphysema, peripheral vessels appear narrowed and widely spaced. Mild to moderate dilatation of central vessels may be present.

Postoperative complications involving the pulmonary circulation are rare. Torsion of a lobe or lung can occur after pulmonary resection, with diaphragmatic hernia and pneumothorax. The angiographic appearance is described in one case, after thoracotomy, as fusiform tapering of the arteries and veins at the site of torsion, with slow vascular filling (35).

**Intraluminal Abnormalities**

**Acute Pulmonary Thromboembolism**
By far the most common indication for pulmonary angiography is suspected pulmonary embolism. The clinical issues relating to diagnosis and treatment of pulmonary thromboembolism are discussed in the Profiles section of Chapter 31. Signs and symptoms, and prior imaging can guide the angiographer to particular lung segments, allowing for the most expeditious examination. A study is considered complete only when a thromboembolus is documented or when a two-view study of both lungs is negative. Primary angiographic evidence of an acute thromboembolus is a persistent central or marginal intraluminal radiolucency, or the trailing edge of an intraluminal radiolucency obstructive to contrast flow (Fig. 13.11). Secondary signs include abrupt cutoff without evidence of an intraluminal defect, oligemic or avascular regions, focal prolonged arterial phase, or abruptly tapered peripheral vessels (Fig. 13.12) (36). Examination for acute pulmonary thromboembolus ideally should be performed within 24 hours of the event. Fragmentation and partial lysis of the thromboembolus may require magnification and subselective angiography for detection of the small residual emboli.

FIG. 13.12.

Secondary evidence of acute pulmonary thromboembolism. (A) Right lower lobe balloon occlusion pulmonary cineangiogram initially demonstrates multiple vessels “cut off” (arrows) as an example of a secondary sign of acute pulmonary thromboembolism. When the balloon is deflated, (B) it becomes apparent the cutoff was the trailing edge of a thromboembolus, with a meniscus evident (arrows). This sign is also considered primary evidence of acute pulmonary thromboemboli.

Methods and devices used in percutaneous mechanical thrombectomy can be utilized to treat selected cases of acute massive pulmonary thromboembolism. The Greenfield transvenous embolectomy catheter (Medi-tech/Boston Scientific, Watertown, MA) has been available the longest, as has balloon maceration of emboli. More recently reported devices range from 14F catheters for suction embolectomy (37), to modified pigtail catheters (38), to rheolytic catheters (39). Operator or local experience probably best determines the method of choice until comparative research determines the relative efficacy of these devices for clot removal and complication.

Chronic Pulmonary Thromboembolism

In a small number of patients, pulmonary thromboemboli fail to resolve, instead organizing, recanalizing, and retracting to variable degrees (Fig. 13.13). Angiographic depiction of location and extent of disease is essential for surgical planning. Surgical thromboendarterectomy of the organized thrombus can improve or cure pulmonary hypertension and right heart dysfunction in severely affected patients. In a study of 250 patients with chronic pulmonary thromboembolism and pulmonary hypertension, Auger and coworkers report the characteristic findings of organized thrombus, confirmed surgically (Table 13.4) (40).

FIG. 13.13.

Chronic pulmonary thromboembolism. Frontal view of right pulmonary angiogram in a 42-year-old female still dyspneic after an acute pulmonary embolus was documented 6 months earlier and treated. The proximal pulmonary arteries are dilated. The distal vessels taper rapidly and are irregular (arrows). Eccentric stenoses are present (arrowheads), as are intraluminal webs (open arrow).

Pulmonary arteriography may not adequately assess the proximal extent of organized thromboemboli. In dilated proximal pulmonary arteries, concentric or smooth organized thromboembolus may mimic the appearance of a normal-sized vessel. Adjunctive imaging of the pulmonary arteries with contrast helical CT was found to be more accurate (0.79) than conventional angiography and MR in the central vessels (41). It is important to note that CT can exclude other causes of multiple stenoses and occlusions of pulmonary vessels, such as chronic infection or inflammation, Takayasu's arteritis, or neoplasm (42) (Fig. 13.14). A combination of imaging modalities may best serve the patient in the workup of chronic pulmonary embolism.

FIG. 13.14.
Histoplasmosis. **A:** Left pulmonary arteriogram in a patient being evaluated for chronic pulmonary thromboembolism. Multiple eccentric stenoses are present (arrows). **B:** Contrast-enhanced CT scan at the level of the left pulmonary artery demonstrates calcified, enlarged lymph nodes (arrowheads) in the region of angiographic abnormality. The mediastinum is diffusely abnormal, containing soft-tissue attenuation material. (Images courtesy of Ulf Nyman, Sahlgrenska University Hospital, Göteborg, Sweden.)

*In situ* central pulmonary arterial thrombosis can occur in severe primary pulmonary hypertension (43). Moser et al. use scintigraphy to distinguish the flow-limiting chronic thromboembolism (segmental defects present), from primary pulmonary hypertension with *in situ* thrombosis (no segmental defects).

### Pulmonary Vascular Neoplasms

Leiomyosarcoma of the pulmonary artery is a rare neoplasm. It typically is seen in the main pulmonary artery in relation to the pulmonary valve. The tumor is entirely intraluminal in half of the reported cases and spreads along the lumen (29). An irregular intraluminal mass is seen at angiography. Metastases to the lung are common.

Pulmonary angiography or hemodynamic assessment may be required preoperatively when other imaging modalities have not answered all questions in mediastinal and perihilar neoplasms. Selective left or right main pulmonary angiograms are usually performed in at least two projections most likely to demonstrate the area of interest based on tumor location. It is important to evaluate the venous phase for any pulmonary venous involvement. Arterial or venous obstruction, encasement, displacement, or rarely intraluminal invasion may be identified.

### Pulmonary Artery Aneurysms

Pulmonary artery aneurysms, defined as a focal increase in diameter of a vessel by 50% over its initial normal diameter, are unusual (44). They can be classified regionally as central or peripheral, in addition to morphologic/anatomic classification as fusiform, saccular, true, and false. The largest number of aneurysms occur centrally, usually secondary to pulmonary hypertension and repairs for congenital heart disease. Congenital aneurysms result from defects in the arterial wall. Degenerative pulmonary aneurysms can be seen in Marfan's syndrome.

Almost any acute or chronic pulmonary infection can lead to the formation of pulmonary arterial aneurysms. Tuberculosis results in pulmonary artery aneurysms known as Rasmussen aneurysms. Other infectious causes of pulmonary artery aneurysms include syphilis and septic emboli. Takayasu's arteritis can rarely cause aneurysms. Multiple pulmonary artery aneurysms may be seen in Behcet's disease or the Hughes-Stovin syndrome (Fig. 13.15) (45). The presence of pulmonary aneurysms in Behcet's disease is associated with a poor prognosis (46). Rupture of pulmonary artery aneurysms usually causes fatal hemorrhage.

**FIG. 13.15.**

Pulmonary artery aneurysms. Frontal view of right pulmonary angiogram in a young male with Hughes-Stovin syndrome demonstrates multiple saccular aneurysms. (Image courtesy of Paul Stark, V.A. Medical Center, Palo Alto, CA.)

Pseudoaneurysms of the pulmonary artery result from penetrating or catheter trauma. These and other aneurysms may be treated percutaneously by exclusion of the pseudoaneurysm sac. Ray et al. report excellent technical and clinical success in percutaneous embolization of pseudoaneurysms with coils, Gelfoam (Upjohn, Kalamazoo, MI), and suture material (47).

### Inflammation

Infectious and noninfectious inflammatory diseases of the lung manifest a spectrum of findings at pulmonary arteriography. Consequently, no single finding is diagnostic of a particular disease. Noninfectious vasculitis involving the pulmonary vessels is uncommon. It can be seen in Takayasu's arteritis, where the degree of involvement has been
correlated with the severity of brachiocephalic disease (48). Findings include stenosis, occlusion, and, rarely, dilatation of pulmonary arteries. CT angiography best demonstrates the wall thickening and enhancement of involved arteries (49). Systemic-to-pulmonary artery communications can exist, with bronchial arteries serving as collaterals to the occluded pulmonary arteries. Yamada and colleagues found most of the disease in the segmental and subsegmental vessels (48). Coronary-to-bronchial-to-pulmonary artery shunts can also occur (50).

Behcet's disease involves the pulmonary arteries with a nonspecific vasculitis in about 5% of patients. Angiographic finding are predominantly aneurysms, with occlusion noted less frequently (46).

In chronic thoracic infections such as histoplasmosis, granulomas can be seen in the walls or arteries, veins, or both on histologic examination. Severe mediastinitis from histoplasmosis can compress and occlude the pulmonary arteries and veins as they traverse the mediastinum. Lymph node involvement can compress adjacent arteries and veins, mimicking chronic pulmonary embolism (Fig. 13.15).

Hemorrhage

Though most life-threatening hemoptysis is of bronchial artery origin, when embolization of the bronchial arteries and other systemic collaterals fails to control hemoptysis, the pulmonary arteries should be examined in the suspected area of hemorrhage (51). Massive hemoptysis can be due to rupture of Rasmussen's aneurysms (52) or to those seen in Behcet's or Hughes-Stovin syndrome (45).

Foreign Bodies

The pulmonary arterial system is the final destination for fractured and embolized medical and nonmedical devices placed in the venous system. In most cases, a formal angiogram is not necessary as most foreign bodies encountered in this setting are radioopaque, but a hand-injected run is helpful to determine the size and orientation of the vessel containing the foreign body. Percutaneous retrieval using a nitinol snare (Microvena, White Bear Lake, MN) is highly effective and has simplified the approach to foreign-body removal. Balloons are well suited to engage lost stents and are used either to deploy the stent in a safe location or to retrieve it via a venous cutdown.