Imaging of the Postsurgical Thoracic Aorta
A State-of-the-Art Review

Larry A. Latson, Jr, MD, MS,*† Abe DeAnda, Jr, MD,‡ and Jane P. Ko, MD*

Abstract: Techniques for repair of the aorta currently include open and endovascular methods, hybrid approaches, minimally-invasive techniques, and aortic branch vessel reimplantation or bypass. Collaboration among radiologists and vascular and cardiothoracic surgeons is essential. An awareness of the various surgical techniques, expected postoperative appearance, and potential complications is essential for radiologists. This review will cover the postoperative appearance of the thoracic aorta with a focus on the ascending aorta. The value of three-dimensional image evaluation will also be emphasized.

Key Words: postoperative, computed tomography, thoracic aorta, aneurysm, dissection, dual energy, high pitch, endovascular repair

LEARNING OBJECTIVES

After completing this CME activity, physicians should be better able to:
(1) Outline surgical and interventional techniques for aortic repair.
(2) Identify postsurgical changes and complications resulting from aortic surgery on imaging.
(3) Describe the role of imaging in postoperative evaluation.
(4) Apply computed tomography (CT) protocols for posttherapy evaluation of the aorta.

Surgical techniques to repair the thoracic aorta have advanced rapidly. Radiology plays an essential role in the follow-up of patients after aortic surgery. Diagnostic radiologists are essential members of a multidisciplinary team comprising vascular surgeons, cardiothoracic surgeons, and interventional radiologists. The postoperative evaluation of these patients can be challenging given the complexity of the surgical and endovascular procedures currently being performed.

Therefore, our objective is to review the normal appearance and potential complications after repair of the thoracic aorta, focusing on open and minimally-invasive surgical techniques. Attention will be primarily directed toward the ascending aorta and aortic arch, open repair, and how to minimize potential interpretive pitfalls.

THORACIC AORTIC ANATOMY

The thoracic aorta is divided into the aortic root, ascending (tubular) aorta, the arch, and the descending thoracic aorta.1,2 About 68% to 74% of patients have conventional aortic arch branch vessel anatomy, and any variations can affect surgical repair.3,4 The innominate and left common carotid arteries arise from the arch as a common origin (sometimes termed a “bovine” arch) in about 21% to 27% of the population. In 3% to 7%, the left vertebral artery arises directly from the arch. Other variants include a left aortic arch with aberrant right subclavian artery and a right aortic arch with either an aberrant left subclavian artery or a mirror-image branching configuration.3,4

Imaging Techniques for Postoperative Evaluation

CT Angiography: Imaging Protocol and Aortic Measurement

CT angiography (CTA) and magnetic resonance angiography (MRA) play a major role in evaluating the aorta after open or endovascular treatment. Protocols should be tailored according to the surgery performed (Table 1). CT angiogram protocols achieve peak contrast enhancement with either a timing run or bolus tracking. Abdominopelvic CTA including the iliac and femoral arteries is used to assess for access site complications in the femoral artery, when cannulated for cardiopulmonary bypass (CPB). With ultrafast imaging, intravascular contrast volumes can be reduced to as low as 50 mL, followed by a saline bolus, to decrease the risk for nephrotoxicity.5

Motion-free images are useful when evaluating the postsurgical aorta. Ultrafast nongated techniques, such as with dual-source or single-source wide-detector array CTs, minimize pulsation artifacts that can mimic dissection and hinder measurement, particularly of the ascending aorta6 (Fig. 1). Alternatively electrocardiogram (ECG)-gated methods can be used, although they are typically associated with higher radiation doses compared with nongated protocols. The routine use of ECG gating therefore may not be warranted and varies among institutions.7,9 ECG-gated...
angiogram protocols are helpful when coronary artery complications, aortic valve anatomy, and perivalvular abscesses and pseudoaneurysms are suspected. Prospective ECG-gated protocols, particularly ultrafast ECG-gated high-pitch ones, result in lower radiation exposure in patients with low heart rates compared with retrospectively gated techniques.\textsuperscript{10,11} Retrospective gating, however, provides information at different phases of the cardiac cycle.\textsuperscript{8}

Precontrast imaging facilitates identification of postsurgical grafts, clips, or felt pledgets (Table 1).\textsuperscript{12} To limit radiation exposure, precontrast imaging can be reserved for the first postoperative examination and confined in the craniocaudal direction to the surgical region. A virtual noncontrast imaging series can be created from a postcontrast dual-energy CT using material decomposition (Fig. 2). Dual-energy techniques entail near simultaneous

### TABLE 1. Imaging Techniques Used for Postoperative Evaluation

<table>
<thead>
<tr>
<th>CT Technique</th>
<th>Potential Use</th>
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<tbody>
<tr>
<td>Delayed imaging</td>
<td>Identify slow endoleak</td>
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<td></td>
<td>Differentiate thrombus from slow flow in false dissection lumen</td>
</tr>
<tr>
<td>Precontrast imaging</td>
<td>For first study after surgical or endovascular repair: for graft/stent location</td>
</tr>
<tr>
<td></td>
<td>For acute symptomatic presentations: better identification and characterization of acute, intramural hematoma, particularly the ascending aorta</td>
</tr>
<tr>
<td>Dual-energy CT</td>
<td>Eliminates the need for precontrast imaging</td>
</tr>
<tr>
<td></td>
<td>“Virtual” noncontrast images: displays postsurgical graft, endovascular stent, and pledgets</td>
</tr>
<tr>
<td></td>
<td>Iodine-enhanced images: displays areas of iodine in an area, such as endoleaks and pseudoaneurysms</td>
</tr>
<tr>
<td>Ultrafast imaging techniques, eg high-pitch CT, wide detector row CT</td>
<td>Minimizes pulsation artifact without gating, if ascending aorta is primarily affected</td>
</tr>
<tr>
<td>ECG-gated imaging</td>
<td>If perivalvular leak or complications in coronary arteries are suspected</td>
</tr>
<tr>
<td>MR Technique</td>
<td></td>
</tr>
<tr>
<td>3D SSFP</td>
<td>Noncontrast free-breathing technique, can be used in patients with severe renal dysfunction</td>
</tr>
<tr>
<td>Cine sequences</td>
<td>For assessment of persistent dissection flap in the descending aorta. Evaluate for functional obstruction</td>
</tr>
<tr>
<td>Phase contrast</td>
<td>Measurement of aortic flow volume and velocity through a specific plane: allows estimation of pressure gradients after coarctation repair, prolonged deceleration time in the descending aorta, and collateral flow distal to coarctation</td>
</tr>
<tr>
<td>Postprocessing Techniques</td>
<td>3D volume rendering: for 3D aortic anatomy, aneurysm location and morphology, and endovascular stent location Centerline and/or double-oblique images: aortic dimensions and/or double-oblique views</td>
</tr>
</tbody>
</table>

Precontrast imaging facilitates identification of postsurgical grafts, clips, or felt pledgets (Table 1).\textsuperscript{12} To limit radiation exposure, precontrast imaging can be reserved for the first postoperative examination and confined in the craniocaudal direction to the surgical region. A virtual noncontrast imaging series can be created from a postcontrast dual-energy CT using material decomposition (Fig. 2). Dual-energy techniques entail near simultaneous

![FIGURE 1. High-pitch mode to reduce motion artifact. A 69-year-old female patient being followed with serial imaging for a dilated ascending aorta. A, Image acquired using standard pitch acquisition. B, Image acquired 1 year later, utilizing a high-pitch technique. Note the decreased motion artifact in the wall of the ascending aorta, main pulmonary artery, and proximal coronary arteries (arrows). Both sets of images are of 1 mm thickness, 100 kVp, using the same amount of contrast material, and were obtained without the use of ECG-gating. The image (B) was reconstructed with iterative reconstruction, accounting for the decreased noise.](image-url)
imaging with low and high tube potentials. Delayed postcontrast imaging, performed during the venous phase at approximately 60 to 90 seconds after beginning the contrast injection, aids in detecting slow endoleaks and in differentiating poor opacification of any remaining false dissection lumen from the thrombus.

Measurement is an essential part of any radiologic assessment of the postsurgical aorta, and measurements can vary up to 1.8 ± 1 mm between the systole and the diastole. The aortic lumen should be consistently measured using the outer wall and acquired at the point of maximal enlargement for each of the aortic regions. The smallest cross-sectional measurement should be used, as a larger dimension can result from oblique orientation of the aorta in the axial plane. Comparison with multiple studies and remeasurement of the aorta, rather than relying on prior reported measures, aid in detecting changes in caliber. Double-oblique off-axial and curved multiplanar reformats with automated center line generation are useful, particularly for the sinus of Valsalva, to achieve measures that are truly orthogonal to the vessel lumen.

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**SURGICAL AND ENDOVASCULAR TECHNIQUES: POSTOPERATIVE APPEARANCE AND COMPlications**

Aortic diseases that require repair and typical criteria for intervention are described in Table 2. The type of therapy undertaken depends on many variables including underlying anatomy, pathophysiology of the aortic disease, acuity of presentation, preferences of the surgeon, availability of certain devices and implants, and techniques in practice at the time of surgery. Knowledge of open surgical and endovascular techniques and their expected postoperative imaging appearance aids in the identification of complications (Tables 3, 4).

**Open Repair**

**Ascending Aorta**

The ascending aorta is most often repaired using an open surgical approach. Aneurysm is a common indication. Operations involve either placement of an inclusion graft within an aneurysm sac or, more commonly now, an interposition graft replacement of the diseased aorta. Ascending aortic grafts often terminate in the distal coronary arteries and intracardiac anatomy, which are typically obscured on conventional MRA (Fig. 3). Newer techniques include unenhanced free-breathing 3D steady-state free precession MRA sequences that do not require breath-holding and gadolinium contrast administration. A “navigator” placed typically over the right hemidiaphragm and dome of the liver allows imaging to occur only when the diaphragm is at the specified level, with reported excellent image quality. MRI is susceptible to magnetic field inhomogeneity, and artifacts caused by metallic stents can be minimized by optimizing the imaging parameters. Phase-contrast imaging is useful for the estimation of any pressure gradient when coarctation is suspected. As with CT, consistent MRA imaging and reporting protocols are needed.
ascending aorta, proximal to the innominate artery. The interposition graft is typically a coated conduit, associated with better anastomotic results and less pseudoaneurysm formation\textsuperscript{1,35} (Table 3 and Fig. 4). The inclusion graft lumen is smaller than the aneurysm sac and creates a “perigraft space” between the graft and aneurysm wall that thromboses. A “Cabrol shunt,” a surgical connection between the aneurysm sac and the right atrium, can be performed to drain blood flow from the perigraft space into the right atrium if excessive bleeding is identified during surgery.\textsuperscript{35} Compression of the graft lumen from an enlarging perigraft space is prevented (Fig. 5).

Associated Aortic Valve Disease: If the aortic root is not enlarged, the ascending aortic aneurysm is repaired with an interposition graft, and simultaneously the diseased aortic valve is replaced with either a mechanical or a bioprosthetic aortic valve (Figs. 4, 6). The Ross procedure is another technique for aortic valve replacement in which the patient’s own native pulmonic valve is moved into the aortic position (autograft). A homograft valve is used to replace the native pulmonic valve\textsuperscript{36} (Fig. 7 and Table 3). The Ross procedure results in a living autologous trileaflet neo-aortic valve and is often favored in younger patients.\textsuperscript{36}

Aortic Root Enlargement and Aortic Valve Disease: Aneurysmal dilatation of both the aortic root and the tubular ascending aorta and an abnormal aortic valve is often addressed with a mechanical or a biological composite valved graft. Regardless of the root replacement technique, the coronary arteries are also typically either reimplanted or bypassed at the time of surgery, with one exception being the Cabrol procedure described below.

First described by Wheat et al,\textsuperscript{37} aortic root replacement has evolved, with Bentall and DeBono developing an
Coarctation Focal narrowing of the aorta Generally repaired if a pressure gradient is not feasible because of severe atherosclerosis of the ascending aorta or proximal coronary arteries (Fig. 5). The Cabrol procedure can be performed to anastomosis of the coronary arteries onto the graft and root with a composite interposition graft and valve and root replacement techniques with diagrams is provided by Prescott-Focht et al.39

**TABLE 2. Aortic Diseases Resulting in Aortic Intervention and Suggestions for Imaging Evaluation**

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Etiologies</th>
<th>Indications for Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aneurysm</td>
<td>Atherosclerotic (main cause in descending aorta)</td>
<td>Size: unless other coexisting conditions</td>
</tr>
<tr>
<td></td>
<td>Age-related aneurysm</td>
<td>Ascending: maximal diameter</td>
</tr>
<tr>
<td></td>
<td>Marfan’s, Turner’s, Ehler’s-Danlos, Loeys-Dietz, other connective tissue diseases and familial aneurysm syndromes, particularly affecting the ascending aorta</td>
<td>≥ 5.5 cm</td>
</tr>
<tr>
<td></td>
<td>Aortic valve stenosis, including bicuspid aortic valve</td>
<td>≥ 4.5 cm with aortic valve disease</td>
</tr>
<tr>
<td></td>
<td>Aortic valve regurgitation</td>
<td>Aortic arch:</td>
</tr>
<tr>
<td></td>
<td>Vasculitis (Takayasu’s, Giant Cell)</td>
<td>≥ 5.5 cm if ascending and/or descending aortic repair also planned</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Descending:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≥ 5.5 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 6 cm if thoracoabdominal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coexisting conditions</td>
</tr>
<tr>
<td>Pseudoaneurysm</td>
<td>Aortic dissection, penetrating atherosclerotic ulcer (PAU), trauma, mycotic</td>
<td>Ascending and arch: typically repaired emergently</td>
</tr>
<tr>
<td>Aortic dissection</td>
<td>Intimal tear resulting in blood flow within the media (false lumen), with subsequent weakening of the aortic wall with risk for pseudoaneurysm and rupture</td>
<td>Descending: traumatic and mycotic typically repaired immediately; surveillance to assess for aortic dissection</td>
</tr>
<tr>
<td>Penetrating atherosclerotic ulcer (PAU)</td>
<td>Atherosclerotic plaque with ulceration through the intima into the media</td>
<td>Type A (involving ascending aorta and/or arch): typically repaired emergently Type B (distal to the left subclavian artery): typically medically managed and followed with imaging unless complications of end-organ ischemia, pseudoaneurysm size meeting criteria for repair, or rupture</td>
</tr>
<tr>
<td>Intramural hematoma (IMH)</td>
<td>Hemorrhage within the media, either through intimal tear and thrombosis in the false lumen, thrombosed dissection lumen, IMH related to PAU, or rupture of vasa vasmorum in the media</td>
<td>Involving ascending and/or arch: typically repaired emergently Descending thoracic aorta: medically managed and followed unless complications are identified, such as dissection, pseudoaneurysm, rupture Often amenable to TEVAR</td>
</tr>
<tr>
<td>Coarctation</td>
<td>Focal narrowing of the aorta</td>
<td>Generally repaired if a pressure gradient ≥ 20 mm Hg across the coarctation or evidence of significant collateral flow</td>
</tr>
</tbody>
</table>

**Normal Aortic Leaflets With Enlarged Aortic Root and Annulus:** Aortic root enlargement can result in aortic regurgitation, even when the valve leaflets are normal. Valve-sparing root replacement techniques are useful.42 Either remodeling of the aortic root or reimplantation of the aortic valve can be undertaken.42 The David procedure and its many modifications consist of reimplanting the native aortic valve within an ascending aortic graft. The Yacoub procedure is a remodeling technique of the sinus of Valsalva in which an aortic graft is cut so that the individual sinuses are replaced while leaving the valve intact.43 Both procedures require coronary reimplantation. An excellent review of various aortic root replacement techniques with diagrams is provided by Prescott-Focht et al.39

**Isolated Aortic Arch or Combined Aortic Arch/Ascending Aorta:** The simultaneous replacement of the proximal arch and ascending aorta can be performed. Total arch replacement, in combination with ascending aortic repair, can be used to treat aortic dissections with significant collateral flow.
complications such as aneurysm or leakage. Arch repair entails reimplantation of the great vessel(s) either onto the native or grafted ascending aorta or onto other great arteries, such as the innominate to the left common carotid arteries. Aortic “debranching” refers to removal of the 3 major branches from the aortic arch and their reimplantation into a trifurcated graft that arises from the ascending aorta (Figs. 9–11).

### Table 3: Typical Aortic Repair Techniques According to Region Involved

<table>
<thead>
<tr>
<th>Regions Involved</th>
<th>General Repair Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascending Aorta</td>
<td>Cardiopulmonary bypass:</td>
</tr>
<tr>
<td></td>
<td>- Aorta clamped proximal to cannula</td>
</tr>
<tr>
<td></td>
<td>- Oxygenated blood return to distal ascending aorta distal to clamp</td>
</tr>
<tr>
<td></td>
<td>- Alternatively, oxygenated blood return to femoral artery, when aortic dissection in arch and descending aorta</td>
</tr>
<tr>
<td></td>
<td>- Circulatory arrest usually not needed</td>
</tr>
<tr>
<td>Tubular ascending aorta</td>
<td>Open surgery</td>
</tr>
<tr>
<td></td>
<td>- Interposition graft</td>
</tr>
<tr>
<td></td>
<td>- Inclusion graft</td>
</tr>
<tr>
<td></td>
<td>- Cabrol shunt occasionally performed to decompress perigraft space</td>
</tr>
<tr>
<td>Tubular ascending aorta, aortic root enlargement ± aortic leaflet disease</td>
<td>Open surgery</td>
</tr>
<tr>
<td></td>
<td>- Aortic valve leaflets abnormal:</td>
</tr>
<tr>
<td></td>
<td>- Bentall procedure</td>
</tr>
<tr>
<td></td>
<td>- When severe atherosclerosis involves the origins of the coronary arteries or aorta surrounding coronary artery origins: Cabrol procedure</td>
</tr>
<tr>
<td></td>
<td>- Aortic valve leaflets without disease (ie, aortic regurgitation from dilatation of aortic root): possibly valve-sparing surgery with coronary reimplantation:</td>
</tr>
<tr>
<td></td>
<td>- David procedure</td>
</tr>
<tr>
<td></td>
<td>- Yacoub procedure</td>
</tr>
<tr>
<td>Tubular ascending aorta, normal root caliber, aortic valve disease</td>
<td>Open surgery</td>
</tr>
<tr>
<td></td>
<td>- Ascending aortic graft (inclusion or interposition) + aortic valve replacement, eg Wheat procedure</td>
</tr>
<tr>
<td></td>
<td>- Ross procedure for aortic valve replacement in young patients</td>
</tr>
<tr>
<td>Aortic Arch</td>
<td>Cardiopulmonary bypass:</td>
</tr>
<tr>
<td></td>
<td>- Oxygenated blood returned to right axillary or innominate artery via cannula for selective cerebral perfusion</td>
</tr>
<tr>
<td></td>
<td>- Typically hypothermic circulatory arrest</td>
</tr>
<tr>
<td>Ascending aorta, proximal aortic arch</td>
<td>Open surgery</td>
</tr>
<tr>
<td></td>
<td>- Ascending and proximal aortic arch graft</td>
</tr>
<tr>
<td></td>
<td>- Great vessel reimplantation into ascending aortic graft or another great vessel branch</td>
</tr>
<tr>
<td>Aortic arch only</td>
<td>Open surgery</td>
</tr>
<tr>
<td></td>
<td>- Aortic graft and arch debranching (arch vessels reimplanted into common graft arising from aorta)</td>
</tr>
<tr>
<td>Aortic arch and proximal descending thoracic aorta</td>
<td>Open surgery</td>
</tr>
<tr>
<td></td>
<td>- Elephant trunk procedure (arch ± ascending aortic grafting, followed by descending aortic graft or endovascular stent (modified elephant trunk)</td>
</tr>
<tr>
<td>Descending Aorta</td>
<td>Cardiopulmonary bypass:</td>
</tr>
<tr>
<td></td>
<td>- Cardiopulmonary bypass may not be needed</td>
</tr>
<tr>
<td></td>
<td>- Oxygenated blood return to ascending aorta or right axillary artery</td>
</tr>
<tr>
<td></td>
<td>- Circulatory arrest usually not needed</td>
</tr>
<tr>
<td>Descending thoracic aorta</td>
<td>Aneurysm:</td>
</tr>
<tr>
<td></td>
<td>- Endovascular repair ± coverage of left subclavian artery</td>
</tr>
<tr>
<td></td>
<td>- Carotid-subclavian bypass graft (if coverage of left subclavian artery) or endovascular techniques (chimney or snorkel) to preserve flow to left subclavian</td>
</tr>
<tr>
<td></td>
<td>- Aneurysm with chronic dissection:</td>
</tr>
<tr>
<td></td>
<td>- Open repair (particularly in connective tissue disorders), possibly endovascular repair</td>
</tr>
<tr>
<td></td>
<td>- Attention to maintaining spinal cord perfusion (ie, prophylactic cerebrospinal fluid drainage)</td>
</tr>
<tr>
<td>Thoracoabdominal aorta</td>
<td>Typically open repair, with vascularization of end organs as needed</td>
</tr>
<tr>
<td></td>
<td>- Attention to maintaining spinal cord perfusion</td>
</tr>
<tr>
<td>Coarctation repair</td>
<td>Resection of coarctation and end-to-end anastomosis or interposition graft</td>
</tr>
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<td></td>
<td>- Patch aortoplasty</td>
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<tr>
<td></td>
<td>- Subclavian flap aortoplasty</td>
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<td>- Stent placement; young adults, adults</td>
</tr>
</tbody>
</table>

### Descending Aorta

**Descending Thoracic Aorta With Aortic Arch Involvement:** The aortic arch and descending aorta cannot easily be addressed during the same surgery (Table 3). Therefore, a 2-step “elephant trunk” repair can be performed. First, the aortic arch is debranched and repaired by means of a median sternotomy. The distal end of the arch graft is left “dangling” within the lumen of the proximal descending
### TABLE 4. Postoperative Imaging Findings and Complications

<table>
<thead>
<tr>
<th><strong>Open Repair</strong></th>
<th><strong>Postoperative Imaging Appearance, Complications, and Pitfalls</strong></th>
</tr>
</thead>
</table>
| **Surgical graft** | Interposition graft:  
High attenuation, difficult to see on contrast CT; some barely visible on noncontrast CT  
Can mimic atherosclerotic disease  
Abrupt caliber change in segment of aorta indicates graft  
Cabrol procedure: focal enhancement adjacent to ascending aorta related to coronary graft to which coronary arteries anastomose  
Inclusion grafts:  
Thrombosed aneurysmal perigraft space, surrounding a normal-sized lumen enclosed by graft  
Can mimic aortic dissection  
Mild indentations at proximal, distal anastomosis  
Pledgets can indicate proximal, distal anastomosis  
Dissection or intramural hematoma repair:  
Dissection or intramural hematoma remains in aorta distal to graft  
Aortic arch branch vessel dissections can be observed  
Cabrol shunt:  
Small connection coursing from perigraft space to right atrium (left to right shunt, decompressing aneurysm sac), typically thrombosed after early postoperative period, but can persist  
Can mimic thrombosed or enhancing pseudoaneurysm; coronal multiplanar reformats helpful for evaluation  
Elephant trunk procedure:  
Graft in the ascending aorta and arch with aortic arch debranching (see below)  
Dangling end of arch graft within the lumen of the descending aorta, mimicking dissection flap (stage I)  
After stage II of repair: extension of graft more distally into the descending aorta (open or endovascular)  
Pledgets:  
High attenuation, at anastomoses site  
Can mimic small pseudoaneurysm on contrast series; precontrast or dual-energy virtual noncontrast imaging useful  
Aortic arch branch vessel reimplantation changes (aortic debranching):  
Common origin of arch vessels from a common graft (arch repairs) and can be bifurcated or trifurcated  
Common graft arises from below the graft in the ascending aorta or occasionally aortic graft  
Subclavian flap aortoplasty (for coarctation) and patch aortoplasty:  
Ligation of the proximal subclavian artery  
Contour abnormality in the region of prior coarctation with subclavian flap aortoplasty  
Dacron patch in the region of coarctation with patch aortoplasty  
Oversewn side arms in grafts:  
Saccular outpouching mimicking pseudoaneurysm, however high attenuation on precontrast imaging  
Clip or pledget at cannulation sites  
Complications and pitfalls:  
Early postoperative complications (within 30 d):  
Edema, pneumonia, acute respiratory distress syndrome  
Infected collections, mycotic aneurysm: enlarged mediastinum. Saccular outpouchings of contrast  
Anastomosis breakdown → mediastinal hematoma, hemothorax: enlarged mediastinum  
Foreign bodies: needles, surgical sponges with linear dense markers within  
Delayed complications:  
Perigraft flow (inclusion graft):  
Enhancement in perigraft space  
Pseudoaneurysm:  
Cardiopulmonary cannulation sites (clips or pledgets, ascending aorta, axillary/subclavian artery depending upon approach)  
Aneurysm sites of aorta grafts, coarctation repair  
Anastomosis sites of aorta grafts, coarctation repair  
Aneurysm enlargement:  
From perigraft flow  
In areas of chronic dissection  
Sternal dehiscence and infection:  
Change in sternal wire alignment over time  
Cabrol shunt patency:  
Possible shunt L → R (ascending aorta to right atrium)  
Infection:  
Low-attenuation collections, gas, aneurysm formation  
Aortoesophageal and aortopulmonary fistula:  
Mediastinal gas bubbles, collection, contrast extravasation  
Recoarctation:  
Aneurysmal dilatation, ascending and descending  
Acute dissection:  
Distal to surgical sites |

**Endovascular Repair**

| **Left subclavian coverage** | **Graft between carotid and subclavian artery**  
Occlusion of proximal left subclavian artery (proximal to left vertebral artery) with thrombus or metallic coil or surgical ligation  
Endovascular stent:  
Radiodense metallic stent in the aorta at the site of aneurysm or coarctation  
Stents in left subclavian artery to maintain patency, when TEVAR proximal to left subclavian artery (eg, snorkel, chimney stent) |
### TABLE 4. (continued)

<table>
<thead>
<tr>
<th></th>
<th>Postoperative Imaging Appearance, Complications, and Pitfalls</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Early complications</strong></td>
<td></td>
</tr>
<tr>
<td>Paraplegia</td>
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<td>Paraparesis, monoparesis</td>
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<tr>
<td>Carotid, verteobasilar strokes from embolic phenomena</td>
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<td>Access vessel thrombosis</td>
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<td>Back pain and leukocytosis</td>
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<td>Renal failure</td>
<td></td>
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<td>Infection, hematoma at surgical sites</td>
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<tr>
<td>Endoleak (see below)</td>
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<td></td>
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<tr>
<td><strong>Delayed complications</strong></td>
<td></td>
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<tr>
<td>Stent migration</td>
<td></td>
</tr>
<tr>
<td>Endoleak</td>
<td>Change in location of stent (measured relative to landmarks like origins of arch vessels)</td>
</tr>
<tr>
<td></td>
<td>Type I: attachment site (proximal and distal ends)</td>
</tr>
<tr>
<td></td>
<td>Type II: branch endoleaks (left subclavian artery, intercostal arteries)</td>
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<tr>
<td></td>
<td>Type III: midgraft holes, stent disruptions, modular stent disconnections</td>
</tr>
<tr>
<td></td>
<td>Type IV: graft porosity</td>
</tr>
<tr>
<td></td>
<td>Type V: endotension—progressive aneurysm enlargement without visible leak</td>
</tr>
<tr>
<td></td>
<td>Can be mimicked by calcification in thrombus within perigraft space (noncontrast CT helpful)</td>
</tr>
<tr>
<td>Aneurysm enlargement</td>
<td>From endoleak or endotension</td>
</tr>
<tr>
<td>Dissection</td>
<td>Retrograde or antegrade dissection flap, detached portion of intimal flap of dissection within lumen</td>
</tr>
<tr>
<td>Kinking, strut fractures</td>
<td>Sharp stent angulation</td>
</tr>
<tr>
<td></td>
<td>Fragments and extraluminal extension</td>
</tr>
</tbody>
</table>

**FIGURE 4.** A 67-year-old male patient with a history of ascending aorta aneurysm after repair with an interposition graft. The proximal and distal anastomoses of the graft create apparent “waists” in the ascending aorta (A, black arrows). On precontrast images, the graft itself is only faintly visible as a rim of mildly high-attenuation material (B, white arrows), whereas on postcontrast images (C) the graft appears as a rim of relative low attenuation with some calcifications in the graft material evident (C, black arrows). The overall change in caliber of the aorta at the graft indicates its presence also. The patient is also status post bioprosthetic aortic valve replacement.
aorta. A new graft can be placed into the dangling elephant trunk during subsequent open or endovascular treatment of the descending aorta 45 (Figs. 9, 10).

Thoracoabdominal Aneurysm Repair: Given the length of aorta involved, thoracoabdominal aneurysms are often repaired with open surgery. Combined open and endovascular therapy and fenestrated endovascular grafts are becoming more commonly used. Descending thoracic and thoracoabdominal aortic aneurysms have been classified by Crawford et al. 46 and refined by Safi and Miller 47 (Table 5). The artery of Adamkiewicz, a major source of spinal cord perfusion, most often arises from the left 9th to 12th intercostal artery. Therefore, Crawford Extent II aneurysms that begin beyond the left subclavian artery and extend to the iliac bifurcation have higher rates of postoperative neurological deficits 47,48 (Table 5). Spinal cord monitoring and prophylactic cerebrospinal fluid (CSF) drainage during open and endovascular repair have been used to lower CSF pressure in the spinal canal and promote spinal cord blood flow. 49 However, CSF drainage is associated with its own complications that include intracranial hypotension, subarachnoid bleeding, subdural hematoma, epidural hematoma, and infection. 48

Open Surgical Coarctation Repair: The type of repair undertaken depends on the coarctation anatomy, the age of the patient at the time of repair, individual preferences of the surgeon, and the available techniques (Table 3). First successfully described in 1945, 50 surgical repair includes resection of the coarctation segment with end-to-end anastomosis (Fig. 3) or placement of an interposition graft (Fig. 12). Other methods include patch aortoplasty, in which a graft is used to enlarge the aorta. Subclavian flap aortoplasty, often performed in infants and children, entails ligation of the left subclavian artery with subsequent rotation of and use of a flap of tissue from this vessel to expand the aortic lumen. 50 Patients with known and/or repaired coarctation require lifelong follow-up, although the recommended frequency of follow-up imaging is not yet clearly determined. 34

FIGURE 5. A 90-year-old male patient with a history of Cabrol procedure approximately 15 years earlier, which involved aortic valve replacement, inclusion graft repair of the ascending aorta, reimplantation of the coronary arteries from a single ostium, and creation of a shunt between the aneurysm sac and the right atrium ("Cabrol shunt"). In this patient, the native (diseased) ascending aneurysm sac (A, white arrows) is seen wrapped around the ascending graft. Angiographic (B) and 60-second delayed-phase images (C) show the ascending aortic graft lumen (black *) compressed by thrombus and perigraft flow (white *) in the aneurysm sac. Contrast enhancement representing perigraft flow is seen better on the delayed images (C) than in the angiographic phase (B); the exact site of perigraft flow origin was not identified. The patient has a thrombosed Cabrol shunt (black arrow, A and white arrow, D), which is a surgically created fistula from the perigraft space of the aneurysm sac to the right atrium, intended to decompress the aneurysm sac in the initial postoperative period and subsequently thrombose. The coronary arteries are supplied by a conduit with a single side-to-side anastomosis (not shown) that branches into right and left coronary artery limbs (black arrows, B and E), which are then anastomosed with the native coronary arteries. Note the severely diseased proximal left anterior descending and left circumflex coronary arteries.
**Imaging and Complications**

**Postoperative Appearance:** Chest radiography evaluation in the postoperative patient should evaluate the size of the mediastinum in comparison with the preoperative examination. Graft material from open surgery is typically not visualized, and clips on portable radiographs may not be clearly seen. Median sternotomy wires and aortic valve replacements can be seen. Metallic areas in bioprosthetic valves are evident on radiography, and some mechanical valves can be radiolucent on radiography.

Description of the aortic graft location and the presence of any bypass grafts should be performed on postoperative imaging evaluation. On contrast-enhanced CT, the graft wall is difficult to identify because of the density of luminal contrast. Precontrast imaging can assist in visualizing the graft, which can be only mildly radiodense and occasionally misinterpreted as aortic wall atherosclerosis (Fig. 4). The graft may not be visualized depending upon the graft material. The only clues may be the presence of sternotomy wires, mediastinal clips, changes in luminal caliber, and small indentations and pledgets at the graft ends. Pledgets are placed to decrease bleeding at anastomosis sites and appear as high-attenuation ovoid densities on CT (Fig. 2).

An interposition graft is often of smaller luminal diameter than the adjacent native aorta. This leads to an abrupt caliber change, particularly in the ascending aorta. Proximal and distal graft anastomoses can appear as small indentations or waists, best identified on coronal or sagittal reformat (Figs. 4, 8, 12).

In the inclusion graft procedure, the graft is located within the aneurysm sac, and therefore the caliber of the aorta remains aneurysmal (Fig. 5, Tables 3 and 4). The perigraft space, formed between the aneurysm sac and the graft, should be thrombosed. In the early postoperative phase, acute hematoma within the perigraft space has high attenuation and gradually becomes isodense.

In the Cabrol procedure, comprising a valved inclusion graft and a coronary artery conduit for coronary reimplantation, the coronary conduit is positioned adjacent to the ascending aorta (Fig. 5). A Cabrol shunt placed at the time of surgery for drainage and decompression of...
FIGURE 7. A 19-year-old man with a history of congenital aortic valve insufficiency. The patient had a history of a Ross procedure 1 year earlier, with placement of the patient’s native pulmonary valve in the aortic valve position (autograft) and a pulmonary valve homograft. A pseudoaneurysm of the left ventricular outflow tract was identified on non–ECG-gated CT angiogram (A and B, white arrows). Note significant motion artifact, which limits characterization of the pseudoaneurysm. The pseudoaneurysm was subsequently repaired with a patch with thrombosis of the pseudoaneurysm (C, white arrows), and the patient received a mechanical aortic valve replacement (C). Follow-up image (D) 9 years after the images in A–C was obtained with non–ECG-gated high-pitch flash mode, demonstrating no evidence of residual or recurrent pseudoaneurysm and absence of any motion artifact compared with the initial CT examination. Calcification of the pulmonary homograft wall is a normal postoperative finding after the Ross procedure (E, black arrow).

FIGURE 8. A 70-year-old man with a history of severe aortic valve stenosis and ascending aortic aneurysm. Routine CT angiogram in oblique sagittal (A) and axial (B) planes demonstrates normal postoperative appearance after a modified Bentall procedure, with a pericardial (tissue) prosthetic aortic valve, and replacement of the ascending aorta with 2 grafts with the typical “waist” at the site of anastomosis (A, black arrows). The coronary arteries have been reimplanted (A, white arrows).
the perigraft space into the right atrium is expected to eventually thrombose in the early postoperative phase. 35

After the first stage of the elephant trunk procedure, a graft in the aortic arch is seen as a thin peripheral density. Proximal to the aortic arch graft, a tubular graft arises from the ascending aorta and anastamoses with the 3 great vessels that have been removed from the aortic arch (aortic debranching). The free distal dangling end of the graft in the descending aorta can be mistaken for a dissection flap if the observer does not have knowledge of the patient’s surgical history or does not correctly identify the signs of aortic debranching and grafting (Figs. 9–11). After stage 2 of the repair, a new surgical graft or endovascular stent is seen in the region of the original flap in the distal aortic arch and descending aorta.

Coarctation repair can result in narrowing and irregular contours that mimic recoarctation (Fig. 3). Thoracotomy rib deformities and surgical clips are clues to the incidence of prior surgery. The regions of narrowing can be assessed for any pressure gradient, if needed, with MRI. 51

In patients who have undergone left subclavian aortoplasty, the proximal portion of the left subclavian will be absent, 52 and the distal subclavian will opacify with collateral flow, often from the vertebral artery.

Complications and Imaging Appearance: Immediate and delayed complications can occur (Table 4). In the early postoperative period, anastomotic leaks leading to mediastinal hematoma and hemothorax, retained foreign bodies, and graft infection are complications common to all aortic procedures. Chest radiography plays a major role in identifying enlargement of the mediastinum, implying hematoma or developing infection. Foreign bodies include needles and surgical sponges, which have curvilinear overlapping linear metallic areas. CT is more sensitive for evaluation. Although potentially occurring earlier, more delayed complications typically relate to pseudoaneurysm, dissection, and rupture for open surgical repairs and endoleak and stent migration for endovascular therapy.

Pseudoaneurysms can compress the aortic lumen or coronary arteries, with subsequent bleeding, fistula

FIGURE 9. A 28-year-old female patient with a history of Marfan syndrome and prior ascending aortic aneurysm. The patient has undergone the first stage of the elephant trunk procedure (A, B, C) comprising aortic arch debranching, with all 3 great vessels (black *) supplied by a trifurcating bypass graft (black *, A) and a graft repair of the ascending aorta and arch (white *). She presented for open repair of her descending thoracic aorta (second stage of the elephant trunk procedure). Note the “elephant trunk” extending into the proximal descending aorta (black arrow), which represents graft material left dangling into the descending aorta to facilitate subsequent descending aortic repair. It is important not to confuse this normal graft material for a dissection flap.
53 The estimated incidence is difficult to determine but has been reported in about 0.5% to 2.0% and even in up to 13% of thoracic aortic surgeries.54–57 Pseudoaneurysms appear as saccular areas of contrast outside the periphery of the aortic wall. Treatment has traditionally been open surgical repair. With the development of newer endovascular devices, percutaneous repair with coils or occlusion devices is now possible. Although current descriptions are limited to mainly individual case reports, these techniques will likely be more commonly performed in the future53 (Fig. 13).

Perigraft low-attenuation collections were described as the most common complication by Sundaram et al59 in a series of patients studied over a span of 6 years after thoracic aortic graft repair. The clinical implications of this finding were quite varied, with some patients demonstrating graft infection or dehiscence that required treatment. Others were asymptomatic and only observed. Infection is suggested by contrast extravasation, and gas bubbles can occur in the mediastinum with infection alone or in combination with esophageoaurtic fistula. Aortopulmonary fistula is another rare complication.59

With inclusion grafts, perigraft flow most commonly occurs at the graft ends and where the coronary buttons anastomose with the graft.59 Calcifications in the perigraft space can mimic enhancement, and precontrast images are useful for differentiating. Perigraft flow can lead to aneurysm sac enlargement. Therefore, measurement of the aneurysm sac diameter is important. An abnormal enhancing perigraft space that surrounds the graft lumen can be potentially misinterpreted as an ascending type A aortic dissection if the interpreter is without knowledge of the inclusion graft procedure (Fig. 5).60 Clinical history and evaluation for any postsurgical material is therefore crucial. Precontrast imaging aids in differentiating high-attenuation acute hematoma from mild perigraft flow. A small number of Cabrol shunts can remain patent and enhance when perigraft flow persists, potentially leading to symptoms from left to right shunt.61 They can be misinterpreted as a small pseudoaneurysm or perigraft flow on contrast CT if one is unaware of the surgical history (Fig. 5).

Dissections can occur in any remaining native aorta between an aortic valve replacement and the ascending aortic graft. Fine curvilinear densities involving the aortic
root therefore can be further investigated with ECG-gated methods and echocardiography. If so, the coronary arteries should be analyzed for involvement by dissection.

Complications after coarctation repair include rupture (Fig. 14), recoarctation, pseudoaneurysm, and aneurysm in either or both the ascending and the descending aorta.\textsuperscript{50,62,63} In a large single-center review of 37 of 235 patients (16\%) with coarctation, a majority of which were repaired, the most common complication was ascending aorta aneurysm in 9\% of 235, whereas descending aneurysm occurred in 4\%.\textsuperscript{64} Acute dissection, pseudoaneurysm, aortobronchial fistula, and mycotic aneurysm also resulted.\textsuperscript{64} Although rare, subclavian steal can develop in patients who have had the proximal left subclavian artery ligated as part of the subclavian flap aortoplasty.\textsuperscript{34} Therefore, the status of the subclavian and vertebral arteries should be evaluated in all patients after coarctation repair.

### TABLE 5. Crawford Classification for Thoracoabdominal Aneurysms\textsuperscript{46,47}

<table>
<thead>
<tr>
<th>Type/Extent</th>
<th>Origin</th>
<th>Termination</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Distal to left subclavian artery</td>
<td>Above celiac axis</td>
</tr>
<tr>
<td>II</td>
<td>Distal to left subclavian artery</td>
<td>Iliac arterial bifurcation</td>
</tr>
<tr>
<td>III</td>
<td>6th intercostal space</td>
<td>Iliac arterial bifurcation</td>
</tr>
<tr>
<td>IV</td>
<td>12th intercostal space</td>
<td>Iliac arterial bifurcation</td>
</tr>
<tr>
<td>V</td>
<td>6th intercostal space</td>
<td>Above renal arteries</td>
</tr>
</tbody>
</table>

**FIGURE 11.** A 75-year-old female status post first-stage elephant trunk repair and cardiopulmonary bypass graft side arms. The patient’s arch was debranched, with a trifurcated bypass graft (A, black \(*)\) to supply the great vessels (B and C, black \(*)\). Two oversewn side arms in the graft are shown, one in the innominate artery (B, black arrow) and a second in the aortic arch graft (C, white arrow), which were cannulated for cardiopulmonary bypass. These grafts are used to maintain cerebral perfusion during portions of the examination and then oversewn by the surgeon. It is important not to mistake these cannulation sites for pseudoaneurysms. A linear density representing a portion of the “elephant trunk” graft extends into the aneurysmal proximal descending aorta (C, black arrow).

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**CPB Techniques and Postoperative Imaging**

Complications can occur from CPB, which is used for oxygenating the blood during surgery. CPB entails central venous cannulation of the right atrium or the vena cava. The blood is oxygenated by the CPB machine, and blood returns to the arterial system in various ways depending on the surgery performed (Table 3). Understanding when CPB is to be used aids in understanding the postoperative appearance on imaging.
For routine ascending and descending aortic replacements, circulatory arrest is not usually needed. Ascending aortic repairs entail CPB with arterial cannulation of the arch or on occasion the innominate or axillary artery. Open surgery on the aortic arch requires interruption of cerebral blood flow. Hypothermic circulatory arrest provides a relatively safe period of time for repair with a bloodless field, and CPB is usually required. More recently, cannulation of the right axillary artery or innominate artery allows selective cerebral perfusion to be performed, through the right common carotid and an intact Circle of Willis. On imaging, clips or pledgets near the right axillary or innominate artery may relate to CPB cannulation sites. Femoral artery cannulation for CPB can be used. For descending aorta replacements, CPB may not be needed at all (the so-called “clamp-and-sew” technique), but when CPB is used the femoral artery is typically utilized for arterial inflow. On occasion, when the distal arch is involved by disease and there is no adequate place to put a clamp proximally, circulatory arrest may be used for descending replacements. The proximal anastomosis of the aortic graft is completed first, and the femoral artery is then used for CPB.

On CT, pseudoaneurysms from CPB appear as focal outpouchings of contrast, often near clips or pledgets that are used to seal the cannulation site (Table 4). Aortic grafts equipped with side arms and side-arm grafts sewn into the axillary or femoral artery for CPB can lead to misdiagnoses of pseudoaneurysm (Fig. 11). Approximately 8 mm in diameter, the side arm of aortic grafts can be cannulated for CPB to perfuse the upper body once the proximal anastomosis of the aortic graft is completed. Similarly, the end of a side-arm graft can be sewn into the side of a right axillary or femoral artery, so that the graft is directly cannulated for CPB rather than the vessel, to minimize vascular and brachial plexus injury. At the completion of the procedure, the side grafts are stapled or oversewn, forming pouches that can mimic pseudoaneurysms (Fig. 11). These pouches have high-attenuation walls on precontrast imaging that can aid in differentiating them from pseudoaneurysms.
FIGURE 13. A 48-year-old male patient with a complicated history of coarctation repair as a child, recurrent endocarditis approximately 6 years earlier, which resulted in multiple aortic and mitral valve surgeries, and new perivalvular leaks/pseudoaneurysms around both valves. Multiple pseudoaneurysms arise from the aortic root (A), a smaller one along the right lateral aspect of the ascending aorta (A, black *), and a large pseudoaneurysm posteriorly (A, white *), with connections to both the ascending aorta and the left ventricular outflow tract (A, white arrows) so that it was initially misinterpreted as the left atrium. The pseudoaneurysms were percutaneously closed using multiple vascular occlusion devices and embolization coils (B, black and white arrows). The proximal left main and left anterior descending coronary arteries are adjacent to the posterior coil mass (B, black arrows). Non-ECG-gated high-pitch technique was critical for reducing motion artifact and for accurately visualizing the complex connections between the pseudoaneurysms and aortic root. Reprinted with permission from Tretter et al.58

FIGURE 14. A 33-year-old female patient with Turner’s syndrome who had undergone aortic coarctation repair in the 1980s when 4 years of age. Chest PA radiograph (A) demonstrates a large saccular aneurysm (white *) in the distal aortic arch, distal to a focal narrowing in the aortic arch consistent with recoarctation (not shown). Surgical repair was planned in stages, with the first stage involving intentional occlusion of the left subclavian artery originating from the proximal portion of the aneurysm sac with an endovascular device (B and E, white arrow). Surgical left carotid to left axillary bypass grafting was also performed to supply the left upper extremity with blood flow. Postoperatively, an acute hemothorax (B and D, black *) occurred, presumed to be related to a rupture of her descending aneurysm. She underwent emergent successful TEVAR (C, D, E) with dilatation of her recoarctation and placement of 2 stent grafts with successful thrombosis of the aneurysm sac (C and D, white *).
Thoracic endovascular aortic repair (TEVAR) is now the preferred technique for descending aortic repair and can also be used for the aortic arch. TEVAR is used primarily to treat aneurysm and traumatic pseudoaneurysms. The United States Food and Drug Administration has approved a variety of stent grafts that differ in terms of material (Nitinol, stainless steel, polytetrafluoroethylene, polyester), required landing zone lengths and diameters, and sheath sizes used for stent delivery.67 Complex fenestrated and branched devices can now be custom manufactured for individual patients for use in the ascending aorta and arch.68

In TEVAR, a stent graft is advanced retrograde from the femoral vessels to the aneurysm sac and placed so that the stent ends form a tight seal with the aortic wall at the landing zones. Isolating the aneurysm sac from the high pressures in the aortic lumen prevents further sac enlargement. The thoracic aorta can be divided into zones, which facilitates accurate evaluation of endovascular therapy outcomes (Table 6).67,69 Intentional coverage of the left subclavian artery can be performed if the proximal aspect of the stent cannot be landed in zone 4, which is 2 cm or more distal to the left subclavian artery.17 The left subclavian artery supplies blood flow to the left upper extremity, brain (through the left vertebral artery), and spinal cord (through the vertebral, internal thoracic, subscapular, and lateral thoracic arteries). Therefore, coverage of the left subclavian artery origin can result in blood flow from the right vertebral artery, through the posterior circulation of the brain and left vertebral artery, to the left subclavian artery. A left-dominant vertebral artery, any

TABLE 6. Aortic Zones Used for Endovascular Repair67,69

<table>
<thead>
<tr>
<th>Zone</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Ascending aorta up to distal end of the origin of the innominate artery</td>
</tr>
<tr>
<td>1</td>
<td>Zone 0 termination to the distal end of origin of left common carotid origin</td>
</tr>
<tr>
<td>2</td>
<td>Zone 1 termination to the distal end of origin of the left subclavian artery</td>
</tr>
<tr>
<td>3</td>
<td>Zone 2 termination to descending aorta &lt;2 cm from the distal aspect of the left subclavian artery origin</td>
</tr>
<tr>
<td>4</td>
<td>Descending aorta &gt;2 cm from the distal aspect of the left subclavian artery origin to distal descending aorta</td>
</tr>
</tbody>
</table>

FIGURE 15. A 68-year-old male patient with no known history of trauma presented with a slowly growing aortic arch aneurysm/pseudoaneurysm over a span of 7 years (A and B, white arrows). Elective repair was performed with TEVAR (C and E, black *). The aneurysm was too close to the origin of the left subclavian artery, and a stent graft was placed proximal to and covering the origin of the left subclavian artery. Instead of a carotid-subclavian bypass, a “chimney” (or “snorkel”) stent was used to maintain flow into the left subclavian artery (C–E, black arrow). 3D volume-rendered image demonstrates the chimney stent in the proximal left subclavian artery (F, white arrow).
absent, atretic, or occluded right vertebral artery, or incomplete posterior circulation can lead to spinal cord ischemia and/or cerebral symptoms (steal phenomenon). Therefore, procedures also address (1) maintenance of blood flow to the upper extremity and spinal cord by performing a carotid to left subclavian artery bypass graft, as suggested by the Society for Vascular Surgery guidelines and (2) prevention of retrograde blood flow from the left subclavian artery into the aortic arch around the endovascular stent (a form of type II endoleak) by ligating or intentional thrombosing the left subclavian artery proximal to the left vertebral artery origin (Fig. 14).

Fenestrated endovascular grafts and other percutaneous techniques are alternate methods used to maintain subclavian artery flow. A number of techniques including the chimney, snorkel, and periscope techniques are possible, in which a stent graft is placed into the left subclavian artery while placing a TEVAR graft (Fig. 15). These have been shown to be safe and effective.

A full description of aortic valve replacement options is beyond the scope of this manuscript. However, transcatheter aortic valve replacement (TAVR), also know as transcatheter aortic valve implantation, or TAVI, is a catheter-based intervention that uses similar techniques as endovascular aortic repair. TAVR is a therapeutic option for inoperable or too high-risk patients with severe symptomatic aortic valve stenosis. Often performed transfemorally, TAVR positions an appropriately sized stent/prosthetic valve complex at the aortic valve. TAVR can also be performed using transsubclavian, transaortic (through an anterior right mini-thoracotomy or partial mini-sternotomy), and transapical (through the apex of the left ventricle) approaches.

Although open surgery is still the preferred technique for correcting coarctations in small and growing children, endovascular repair is now a safe and effective alternative in older children and adults. Balloon angioplasty alone has been used but is complicated by high rates of aortic wall injury and recoarctation. Both bare metal and covered stents have been used successfully, but in the United States, as of yet, no balloon expandable covered stents for coarctation repair are Food and Drug Administration approved.

**Imaging Implications and Complications**

Postoperative Appearance: The chest radiograph, often obtained in the early postoperative period, displays the location and contour of endovascular stents. The number of aortic stents can be evaluated, although multiple overlapping units often limit assessment. Any change in the mediastinal contours can result from hematoma related to aortic rupture or mediastinal infection. After endovascular aortic repair, the stent is located within the aneurysm sac on CT. As with the surgical inclusion graft, the space intervening after successful repair comprises the hematoma. The hematoma is high attenuation in the acute phase when the blood around the stent
clots and then becomes soft tissue attenuation in the chronic phase. Volume-rendered images display the number of stents and areas of overlap better than multiplanar reformats. The stent struts should not extend beyond the aortic lumen contour. Evaluation for aortic branch vessel patency and any bypass grafts is needed. Contrast enhancement of the left vertebral and subclavian arteries is important to assess when the left subclavian artery origin has been covered. Intentional occlusion of the left subclavian artery appears as low-attenuation thrombus or metallic occlusion coils near the vessel’s origin. After TAVR, the prosthetic aortic valve can be seen on radiographs as a metallic mesh in the region of the aortic valve, appearing similar to a metallic stent graft (Fig. 16).

Complications and Imaging Appearance: Immediate complications include aortic injury, dissection, and rupture (Table 4). Peripheral vessels used for placing the stent can have similar complications. A very rare complication, detachment of an aortic dissection flap with distal vessel occlusion can occur during the procedure or early postoperative period, leading to an intraluminal defect and distal vessel obstruction on CT.77

After stent graft placement, assessment for endoleak is mandatory. Endoleak refers to contrast within the excluded aneurysm sac, external to the endovascular stent.17 Endoleak can lead to progressive aneurysm enlargement (Table 4 and Fig. 17). In the thoracic aorta, type I endoleaks occur at the proximal (type 1a) and distal (type 1b) stent ends. A tight seal at the proximal stent end is more difficult to achieve in the thoracic aorta, given the curvature of the proximal descending aorta and arch. Type II endoleaks, which are vessel inflow leaks, are often better seen on delayed images and derive from intercostal arteries or backflow from the left subclavian artery. Contrast from feeding vessels can be seen in the periphery of the thrombus in the excluded aneurysm sac. Type III endoleaks relate to holes or fractures in the middle of the graft or junctional leaks where the stents overlap, with contrast collections near the outer stent wall. Calcifications within thrombus in an aneurysm sac can mimic an endoleak on postcontrast images, and precontrast imaging can help differentiate.17

Although infrequent, other potential complications after TEVAR include stent graft kinking, stent graft migration, and dissection.78 Graft kinking can be

FIGURE 17. Examples of endoleaks types I to III. A, An 87-year-old male patient with contrast extending outside the proximal portion of the endovascular stent graft (white arrow), consistent with a type la endoleak. B, A 57-year-old male patient with a contrast collection within the excluded portion of the aneurysm sac (black *), supplied by retrograde flow in a small intercostal artery (white arrow), consistent with a type II endoleak. C, A 67-year-old male patient with contrast extending between the struts of the stent graft in the descending aorta (white arrows), consistent with a type III endoleak.
potentially seen on chest radiograph as a change in contour of the stent, and migration can be detected by comparing serial imaging. Kinking occurs particularly in areas of aortic tortuosity, predisposing to focal luminal narrowing, stent breakage, and type III endoleak.\textsuperscript{17} 3D volume-rendered CT images help identify kinking and aortic morphology.\textsuperscript{17} As the aorta naturally enlarges and elongates with age, stent graft migration can occur and lead to branch vessel occlusion. Measuring the distance between the endovascular stent and a fixed reference point such as the left subclavian artery origin aids in detecting migration on endovascular stent and a fixed reference point such as the vessel occlusion. Measuring the distance between the endovascular stent, and migration can be detected by comparing with age, stent graft migration can occur and lead to branch stent breakage, and type III endoleak.\textsuperscript{17,67} 3D volume.

Complications after TAVR include paravalvar leak, which is a gap created when the walls of the valve fail to closely approximate the aortic annulus, resulting in aortic regurgitation.\textsuperscript{73} Other complications are coronary ostia obstruction from displaced native aortic valvular calcifications, interference of the anterior mitral leaflet by the aortic valve stent, and prosthetic valve leaflet thrombosis.\textsuperscript{81,82} ECG-gated CTA is an ideal method for postprocedural assessment of TAVR valves, as MRI and echocardiography can be limited by metallic artifact.\textsuperscript{81}

CONCLUSIONS

Open surgical, endovascular, and hybrid approaches to thoracic aortic surgery are increasingly complex. Imaging has an essential role in the postoperative evaluation of the thoracic aorta. Protocols and image evaluation can be tailored to the clinical question using a variety of CTA and MRA imaging methods. Knowledge of the original underlying disease and the repair techniques in use are essential for accurate postoperative imaging interpretation.

REFERENCES

SA-CME EXAM

“Imaging of the Postsurgical Thoracic Aorta: A State-of-the-Art Review”

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SA-CME EXAMINATION QUESTIONS

Question 1

Ascending aortic aneurysm repair is now most commonly performed using:

a) TAVR
b) Inclusion graft technique
c) Interposition graft technique
d) TEVAR

Please see the following references for further study:


Question 2

Side arm cannulation grafts, which are used to provide perfusion of oxygenated blood during cardiopulmonary bypass, are often oversewn at the completion of the procedure and can mimic what finding on CT angiography?

a) Pseudoaneurysm
b) Endoleak
c) Dissection
d) Intramural hematoma

Please see the following references for further study:


Question 3

Aortic debranching entails reimplantation of which vessel(s)?

a) Left common carotid artery
b) Left subclavian artery
c) Right innominate artery
d) All three great vessels
Please see the following references for further study:

**Question 4**
The elephant trunk procedure results in a finding that can be misdiagnosed as a(n):

a) Aortic dissection  
b) Intramural hematoma  
c) Pseudoaneurysm  
d) Stricture

Please see the following references for further study:

**Question 5**
The Ross procedure entails:

a) Replacing the aortic valve with the patient’s native pulmonary valve, which is replaced with a homograft.  
b) Replacing the ascending aorta with a composite interposition graft.  
c) Valve sparing surgery.  
d) Shunt between aneurysm sac and the right atrium.

Please see the following references for further study:

**Question 6**
Delayed CT imaging aids in the detection of which type of endoleak?

a) I  
b) II  
c) III  
d) IV

Please see the following references for further study:

**Question 7**
What is the smallest amount of distance needed for the proximal landing zone when descending aortic endovascular repair without arch coverage is considered?

a) 1 cm  
b) 2 cm  
c) 3 cm  
d) 4 cm

Please see the following references for further study:
Question 8
Which of the below criteria make asymptomatic ascending aortic aneurysms that are 4 to 5 cm eligible for repair?

a) Growth rate 1 mm/year
b) Growth rate 2 mm/year
c) Marfan syndrome
d) Chronic aortic dissection

Please see the following references for further study: