Advances in computed tomography (CT) scanners and electrocardiographic gating techniques have resulted in superior image quality of the ascending aorta and increased the use of CT angiography for evaluating the postoperative ascending aorta. Several abnormalities of the ascending aorta and aortic arch often require surgery, and various open techniques may be used to reconstruct the aorta, such as the Wheat procedure, in which both an ascending aortic graft and an aortic valve prosthesis are implanted; the Cabrol and modified Bentall procedures, in which a composite synthetic ascending aorta and aortic valve graft are placed; the Ross procedure, in which the aortic valve and aortic root are replaced with the patient’s native pulmonary valve and proximal pulmonary artery; valve-sparing procedures such as the T. David–V technique, which leaves the native aortic valve intact; and more extensive arch repair procedures such as the elephant trunk and arch-first techniques, in which interposition or inclusion grafts are implanted, with or without replacement of the aortic valve. Normal postoperative imaging findings, such as hyperattenuating felt pledgets, prosthetic conduits, and reanastomosis sites, may mimic pathologic processes. Postoperative complications seen at CT angiography that require further intervention include pseudoaneurysms, anastomotic stenoses, dissections, and aneurysms. Radiologists must be familiar with these procedures and their imaging features to identify normal postoperative appearances and complications.

Introduction

Several abnormalities of the ascending aorta and aortic arch, including aneurysm and dissection, often require surgical treatment. A variety of procedures are available to repair the thoracic aorta, including placement of a supracoronary ascending aortic graft, with (Wheat procedure) or without placement of an aortic valve prosthesis; placement of a composite artificial graft (Bentall and Cabrol procedures); implantation of a biologic graft (Ross procedure and cadaveric graft); placement of an ascending aortic graft with preservation of the native valve (David valve-sparing...
technique and its derivatives); and arch repair (elephant trunk procedure). In this article, we discuss several open-repair techniques and their indications. We also discuss their normal and abnormal postoperative appearances at computed tomographic (CT) angiography.

**Evaluation of the Postoperative Aorta**

Routine evaluation of the aorta is most frequently performed with CT angiography. Unlike conventional angiography, CT angiography is relatively noninvasive and provides superior image quality, including multiplanar and three-dimensional reformation capabilities (1). In addition, it may depict the mediastinum, allowing diagnosis of alternative intrathoracic complications or abnormalities (1). CT angiography techniques that are optimized to the arterial phase of imaging use a high intravenous contrast material flow rate and contrast material with high iodine content. Injection of contrast material into a right antecubital vein is preferred to avoid streak artifact from venous inflow in the region of the left brachiocephalic vein. Cardiac motion artifacts may be pronounced in the ascending aorta, particularly at the level of the coronary sinuses, and vary depending on the imaging technique. Use of electrocardiographic (ECG) gating or triggered acquisition of data sets allows data to be acquired during a specific phase of the cardiac cycle and cardiac motion artifacts that may simulate disease (eg, aortic dissection) to be removed (2). These techniques are particularly crucial in evaluating patients with a history of coronary reimplantation or aortic valve conditions. Use of an overlapping pitch (ie, a low table speed with a pitch of 0.1–0.3) to acquire data enables retrospective reconstruction of images at varying phases of the cardiac cycle (retrospective gating) and provides superior image quality (ie, improved temporal resolution), although the radiation dose increases as pitch factor decreases (3). Prospective gating techniques use ECG-gated acquisition during only a specified portion of the cardiac cycle, which uses a lower radiation dose than retrospective gating with no motion artifacts. Dual-source CT scanners allow fast data acquisition with both x-ray tubes at the same time, with an overlapping pitch of more than 1.8, minimizing cardiac motion artifacts with no increase in radiation exposure. The choice of imaging technique for assessment of the postoperative aorta requires an understanding of the surgical procedure and its complications.

**Indications for Treatment**

Surgical repair of the ascending aorta is most commonly performed in patients with aortic aneurysm or an acute aortic syndrome (eg, aortic dissection and intramural hematoma). In patients with an ascending aortic aneurysm, the risk for rupture, dissection, or death increases with the size and approaches 14.1% in those with a 6-cm thoracic aortic aneurysm (4). Signs and symptoms associated with aortic aneurysm include aortic insufficiency, chest pain, back pain, and tachycardia (5). Generally, elective surgery is performed in patients with an ascending thoracic aorta aneurysm when the diameter exceeds 5.5 cm (4–6). Earlier surgical intervention is warranted in patients with Marfan syndrome or bicuspid aortic valves, and it is recommended when the diameter of the ascending aorta is larger than 5.0 cm (4–6). Surgical intervention is also recommended in patients with an aneurysm that grows more than 0.5 cm in 1 year (5,6). In addition, in asymptomatic patients, aneurysms are repaired regardless of size (4,5). In patients with an ascending aorta dissection, surgery is performed because of the associated risk for progression, aortic rupture, and cardiac tamponade (5). Aortic intramural hematomas, often considered a variant of aortic dissections, are classified and managed similarly to aortic dissections (5).

**Procedures and Anatomy of Components**

Surgical repair techniques of the aorta include reconstruction with a supracoronary ascending aortic graft, with (Wheat procedure) or without placement of an aortic valve prosthesis; reconstruction with a composite artificial graft (eg, Bentall and Cabrol procedures); reconstruction with a composite biologic graft (eg, Ross procedure and reconstruction with a homograft); reconstruction with an ascending aortic graft with preservation of the native valve (David valve-sparing technique and its derivatives); and arch repair (eg, elephant trunk procedure and arch-first technique). In most
types of graft repair, the diseased native aorta is excised and a biologic or synthetic graft placed. The graft is then reanastomosed to the native anatomic structures. This procedure is known as an interposition graft. In inclusion grafts, the native aorta is wrapped around the synthetic graft, a procedure that is not commonly performed because of the improved surgical techniques achieved with interposition grafts.

Synthetic grafts are most commonly composed of polyethylene (Dacron) and are slightly hyperattenuating relative to the native aortic wall at unenhanced CT (Fig 1a). At contrast material–enhanced CT, grafts are hypoattenuating relative to the aortic lumen and the surrounding felt ring in the arterial phase (Fig 1b) (7). Although grafts may be obscured at CT angiography, their position usually may be determined on the basis of the presence of a change in contour in the aorta or hyperattenuating felt rings along the anastomosis sites (Fig 1c) (7). Because felt is hyperattenuating, it may be mistaken for a pathologic condition, such as a pseudoaneurysm, at contrast-enhanced CT; for this reason, acquisition of unenhanced images is crucial when evaluating patients with a history of aortic repair (Fig 2) (7). Pseudoaneurysms, on the other hand, typically appear iso- or hypoattenuating.
Figure 2. Appearance of felt at CT. (a) Axial contrast-enhanced CT image shows hyperattenuating felt material at the anastomosis site (arrow), a finding that may mimic pseudoaneurysm. (b) Unenhanced CT image more clearly shows the felt material (arrow).

Figure 3. The Wheat procedure. Diagram shows the Wheat procedure, in which an ascending aortic graft (green section) is placed distal to the coronary ostia. A separate aortic valve prosthesis (blue section) is simultaneously placed.

Normal postoperative CT angiography findings seen in all types of open repair include perigraft fluid and perigraft soft-tissue attenuation (7). However, infection should be suspected if associated contrast enhancement, intrinsic air, or a fluid collection that increases in size is seen (7). In addition, normal postoperative air should resolve on its own; persistent (longer than 6 weeks), new, or increasing perigraft air may indicate infection with a gas-producing organism or a fistula with the adjacent bronchus or esophagus (7).

Supracoronary Grafts
An ascending aortic graft that is placed distal to the coronary ostia is known as a supracoronary graft. In 1964, Wheat and colleagues (8) described simultaneous placement of a supracoronary aortic graft and an aortic valve, a technique known as the Wheat procedure (Figs 3, 4). Supracoronary grafting is indicated in patients with an ascending aortic aneurysm of atherosclerotic origin and normal sinuses of Valsalva (9). With this technique, preservation of the coronary ostia minimizes the risk for pseudoaneurysms, stenosis, thrombosis, and kinking at the coronary anastomosis site (8). One recognized complication of supracoronary grafting is the development of dissection or aneurysm of the native aorta proximal to the graft. Patients with annuloaortic ectasia or Marfan syndrome are especially prone to such a complication; thus, a composite repair method (ie, graft plus valve) is typically preferred in such patients (Fig 5) (9,10).
Composite Artificial Grafts
In 1968, Bentall and De Bono (11) developed a procedure for patients with both aortic valvular disease and dilatation of the sinuses of Valsalva whose aortic root walls were too vulnerable to allow suturing of the proximal end of the aortic prosthesis. In the Bentall procedure, the native aortic root and aortic valve are replaced with a composite graft that consists of both ascending aortic and aortic valve grafts and into which the coronary arteries are anastomosed (12).
The relatively common development of pseudoaneurysms at the coronary artery anastomosis sites led to the creation of the modified Bentall procedure, which is also known as the “button Bentall” or “Carrel patch” procedure, in which a “button” of the aorta encircling the coronary ostia is removed with the coronary arteries and anastomosed with the composite ascending aortic (green section) and aortic valve (blue section) graft. Although some authors have claimed that coronary ostial pseudoaneurysms are virtually eliminated with this modified technique, others have reported that they are especially common in patients with Marfan syn-

**Figures 6, 7.** (6) Modified Bentall procedure. Diagram shows the modified Bentall procedure, also known as the “Carrel patch” procedure, in which a “button” of the aorta encircling the coronary ostia is removed with the coronary arteries and anastomosed with the composite ascending aortic (green section) and aortic valve (blue section) graft. (7) Normal postoperative appearance of the modified Bentall procedure. (a–d) Axial CT angiograms show right (arrows in a and b) and left (arrows in c) coronary buttons, felt (arrowheads in d) at the distal anastomosis site, and a prosthetic valve. (e) Oblique sagittal maximum intensity projection reformatted image shows the proximal (arrowheads) and distal (arrows) anastomosis sites and the prosthetic valve.
Pseudoaneurysm at the proximal anastomosis site in a 61-year-old man who underwent the modified Bentall procedure. Axial (a–d) and oblique sagittal reformatted (e) CT angiograms show a large pseudoaneurysm (*) anterior to the ascending aortic graft (a). The distal anastomosis (arrowheads in e) is intact.

The Cabrol procedure was developed in 1981 as an alternative to the modified Bentall procedure in patients with aortic dissection, annuloaortic ectasia, or atherosclerotic aneurysm and in whom the button Bentall technique is not achievable, such as those with severe atherosclerosis of the ascending aorta, which precludes good-quality aortic buttons; severe proximal coronary artery disease; and a failed Ross procedure (16,17). In the Cabrol procedure, a composite aortic root and aortic valve graft and a prosthetic conduit anastomose the coronary ostia to the aortic graft in a side-to-side manner (Fig 9) (17). The normal postoperative appearance of a retroaortic conduit may mimic that of an intimal flap related to aortic dissection; thus, knowledge of the patient’s surgical history is crucial (18). Intrinsic complications of the Cabrol procedure include early postoperative death in patients with aortic dissection, anastomotic leak, coronary graft insufficiency from kinking or intimal hyperplasia, acute coronary graft thrombosis, and endocarditis (Fig 10) (17).
Figure 10. Obstructed right coronary limb in a 69-year-old man who underwent the Cabrol procedure. Consecutive axial CT images show a patent left coronary limb (arrowhead in c and d) and nonopacification of the occluded right coronary limb (arrows), an intrinsic complication of the Cabrol procedure.

Biologic Grafts
The Ross procedure is performed in young patients with a dilated aortic root and an aortic valve condition by replacing the native aortic valve and aortic root with the patient’s own pulmonary valve and proximal pulmonary artery and the pulmonary autograft with a synthetic or biologic pulmonary graft (19). Advantages of the Ross procedure over the use of a prosthetic aortic valve include improved hemodynamics, a lower risk for endocarditis, lower thrombogenicity, an allowance for growth potential in children, and a decreased need for anticoagulation therapy (19). Aneurysmal dilatation of the aortic root is the most frequently reported complication of the Ross procedure (Fig 11). Aortic dissection and pseudoaneurysms at the proximal or distal anastomosis sites have also been described (19).

Aortic Valve–Sparing Procedures
The aortic valve–sparing procedure was introduced by Yacoub in the early 1980s (20) and is an alternative in patients with ascending aortic conditions. It is indicated in patients with an aneurysm at the level of the sinuses of Valsalva, with or without coexisting aortic valvular insuf-
Aneurysmal dilatation of the aortic root in a 24-year-old woman who underwent the Ross procedure. Axial (a–d) and oblique sagittal reformatted (e) CT angiograms show marked dilatation of the ascending aorta and sinuses of Valsalva (arrows in e).

Figure 12. Aortic valve–sparing procedure. Diagram shows the valve-sparing procedure, in which the native aorta is removed, a Dacron graft fastened below the native valve, and the valve reimplemented within the graft.

The aortic valve–sparing technique is especially attractive in patients with Marfan syndrome, not only because such patients are often young at the time of surgery, but also because they are prone to coronary pseudoaneurysm formation after the modified Bentall procedure (15).

In the original remodeling technique developed by Yacoub (20), the aneurysmatic aorta is removed to the level of the annulus, with the aortic valve left intact and the sinuses of Valsalva reconstructed with a Dacron graft. Subsequently, David and Feindel (20) developed a reimplantation valve-sparing technique, in which the native aorta is removed, a Dacron graft fastened below the native valve, and the native valve reimplemented within the graft, rather than reconstructing the sinuses of Valsalva around the valve (Fig 12). This technique has been especially beneficial in patients with acute type A aortic dissection and annuloaortic ectasia (22).
Two modifications of the reimplantation technique have been described. In the T. David–V technique, a larger graft is used to construct pseudosinuses of Valsalva, and in the Demers and Miller modification, two grafts (an aortic root graft with a large diameter and a smaller distal graft) are sewn together to create pseudosinuses that are larger than those created in the T. David–V technique and enable the native valve to be sutured inside the graft (23).

Aortic insufficiency is the most frequently cited complication of valve-sparing procedures (21). In two different studies, David and colleagues (21,24) compared outcomes in patients who underwent the reimplantation technique with those who underwent the remodeling technique and reported that the reimplantation technique resulted in fewer cases of late aortic insufficiency. In patients who undergo reimplantation, postoperative CT angiography is enhanced by using techniques that minimize cardiac motion to allow complete evaluation of coronary artery anastomoses and other anastomotic complications (22).
Figure 14. The classic elephant trunk procedure. (a) Sagittal oblique reformatted CT angiogram shows the normal postoperative appearances of stage I of the classic elephant trunk procedure, in which the distal tip (arrowheads) of the graft (G) is left “floating” within the native descending aorta. A debranching graft (white arrow) and residual dissection (black arrow) are also seen. (b) Sagittal oblique reformatted CT angiogram shows the normal postoperative appearances of stage II of the classic elephant trunk procedure, in which an additional graft (arrows) is anastomosed to the initial graft. Note that the dissected aorta has been excised.

Arch Repair

Extensive thoracic aortic aneurysms are repaired with the elephant trunk procedure, which was described by Borst et al in 1983 (25) and is indicated in patients with atherosclerotic or inflammatory aortic aneurysms involving the arch and descending aorta, postdissection aneurysms, or acute type A aortic dissections. The elephant trunk procedure consists of two stages. In stage I, the ascending aorta and aortic arch are repaired with a median sternotomy, in which the native aorta is removed and a graft placed into the ascending aorta and proximal descending aorta (26). Three anastomoses are created: a proximal anastomosis in the ascending aorta, an intermediate anastomosis with the brachiocephalic vessels, and a distal anastomosis distal to the left subclavian artery takeoff point (Fig 13) (27). Some authors advocate the use of a brachiocephalic debranching procedure during stage I, in which the brachiocephalic vessels are removed from the native aortic arch and attached to the cranial end of a bypass graft (28). The caudal end of the bypass graft is then anastomosed with the proximal aspect of the ascending aortic graft (Fig 14) (28). Debranching the great vessels decreases the duration of cardiopulmonary bypass and aortic cross-clamping, minimizes the risk for renal or visceral ischemia, and increases the proximal landing zone for potential endovascular procedures (28,29). At the conclusion of stage I, the distal end of the graft is left unattached and floats freely in the native descending aorta (27). In stage II, a second graft is placed within the descending or thoracoabdominal aorta by way of a left thoracoabdominal incision and anastomosed with the distal graft from stage I (26). Alternatively, fixation of the distal graft may be achieved by deploying an endograft, the so-called hybrid elephant trunk procedure (30).

Complications of stage I of the original elephant trunk procedure include early rupture at the distal anastomosis site, an air embolism in the distal aorta, and recurrent left-sided laryngeal nerve injury that leads to vocal cord paralysis (25,27,31,32). Spinal cord ischemia leading to...
paraplegia is the most feared complication of stage II, and aortic rupture, and even death, have been described in a relatively high number of patients in the interval between stages I and II (25,27,31). In addition, many patients choose to forgo stage II of the procedure (31). For these reasons, several modifications have been made to the original elephant trunk procedure. In the so-called hybrid technique, the original median sternotomy is used to repair the ascending and transverse aorta, but instead of leaving the distal graft unattached, the descending aorta is repaired with an endovascular approach (26). When performed at the same time, the hybrid technique may decrease overall mortality by decreasing the risk for aortic rupture, which may occur between stages I and II of the traditional procedure. Unfortunately, the development of permanent neurologic deficits remains a significant complication of both the original and hybrid elephant trunk procedures (26).

To minimize the risk for cerebral ischemia, a one-stage surgical approach known as the “arch-first” technique is an alternative to the elephant trunk procedure. With the arch-first technique, the arch vessels are removed from the native aortic arch and reanastomosed to a tubular graft, allowing early antegrade perfusion of the arch vessels. After reanastomosis, the distal end of the branched graft is sutured to the normal native descending aorta, allowing for distal perfusion. Finally, the proximal aspect of the branched graft is anastomosed to a normal-caliber aortic root, a pre-existing ascending aortic graft, or a newly positioned ascending aortic interposition graft. The arch-first technique eliminates the risk for aneurysm rupture and that associated with a second thoracic aortic procedure and has a lower rate of reintervention. It also has lower mortality and morbidity rates than the elephant trunk procedure (33–37).

Conclusion

A variety of open surgical techniques are used to repair thoracic aortic aneurysms. Because normal postoperative appearances may mimic those of pathologic conditions and because several postoperative complications exist, radiologists must be familiar with these procedures and their complications.


References

Ascending Thoracic Aorta: Postoperative Imaging Evaluation
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