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Role of Computed Tomography in Assessment of the Thoracic Aorta

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Opinion statement

Thoracic aortic disease is increasing in prevalence and can result in serious morbidity and mortality. Computed tomography (CT) angiography is an important imaging modality for assessment of thoracic aortic pathology due to wide availability, rapid acquisition, reproducibility, superior spatial and temporal resolution, and capability for 3D image post-processing. CT is the preferred imaging modality in the acute setting to rapidly identify patients with acute aortic syndromes including dissection, intramural hematoma, and penetrating aortic ulcer. CT also plays an important role in post-procedural surveillance of the thoracic aorta for early and late complications from open or endovascular repair. Incidentally detected thoracic aortic aneurysms and congenital aortic anomalies such as coarctation can be thoroughly characterized and followed over time for potential elective intervention. Drawbacks of CT include exposure to radiation and iodinated contrast media; however, recent strategies for dose reduction and contrast optimization have significantly decreased these risks. Electrocardiogram (ECG)-gated CT angiography provides additional information about the aortic root, coronary arteries, and other cardiac structures without motion artifacts.

Introduction

Thoracic aortic disease is increasing in prevalence worldwide and can result in significant patient morbidity and mortality. Data from the Centers for Disease Control demonstrate that diseases of the aorta and large vessel branches are the cause of up to 47,000 deaths annually in the USA [1]. The proportion of these due to thoracic aortic pathology is not well defined, but autopsy studies suggest that thoracic aortic dissection or rupture may cause twice as many deaths annually as ruptured abdominal aortic aneurysms [2•]. The historical use of angiography for evaluation of the thoracic aorta has been supplanted by cross-sectional imaging, with computed tomography (CT) the most readily available and commonly used modality [3]. Newer techniques including multidetector-row CT, electrocardiogram (ECG)-gated CT acquisitions, and image post-processing have allowed increasingly detailed and thorough evaluation of thoracic aortic pathology. CT is essential for the prompt identification of thoracic aortic pathology and triage to appropriate management. There have also been significant advances in repair of thoracic aortic disease using novel open and endovascular techniques for which CT plays an important role in ongoing surveillance for post-procedural complications. In this review, the role of CT in assessing thoracic aortic aneurysms, acute aortic syndromes (AAS), and congenital anomalies will be addressed. Additionally, post-procedural imaging surveillance of the thoracic aorta will be highlighted.

Normal anatomy

The thoracic aorta can be divided into the aortic root, ascending aorta, arch, and descending aorta. The normal aortic root arises from the base of the heart and includes the annulus, aortic valve, and three sinuses of Valsalva. The right and left coronary arteries normally arise from the right and left sinuses, respectively, with the third sinus known as the non-coronary or posterior-facing. The ascending aorta extends from the tapering above the sinuses of Valsalva known as the sinotubular junction to the first branching great vessel, typically the brachiocephalic artery, also known as the innominate artery. The most common arch branching pattern has three separate vessel origins for the brachiocephalic, left common carotid, and left subclavian arteries. Other frequent variants include a common origin of the brachiocephalic and left common carotid arteries, also known as a "bovine arch," or a separate origin of the left vertebral artery directly from the arch. These variants are of no clinical significance. Variant arch anatomy of clinical significance will be discussed below under congenital anomalies. The aortic arch becomes the descending aorta at the level of the aortic isthmus, located between the left subclavian artery and the ligamentum arteriosum. The ligamentum arteriosum is located in the proximal descending aorta and is the site where the ductus arteriosus communicated with the aorta in utero. The descending thoracic aorta extends inferiorly to the diaphragmatic hiatus.

The aortic wall is made up of three layers: the innermost intima which abuts the lumen and is made up primarily of endothelial cells, the medial layer containing smooth muscle and elastic fibers, and the external adventitial layer composed primarily of connective tissue and

containing the blood supply of the aorta, the vasa vasorum. Atherosclerotic plaque and calcifications are located within the intimal layer. The amount of thoracic aortic atherosclerotic plaque is linked to outcomes after major surgery such as coronary artery bypass grafting independent of acute aortic pathology [4].

Normal thoracic aortic dimensions vary by age, gender, and body habitus [5•]. In clinical practice, the thoracic aorta is measured at seven standard locations: the annulus, the sinuses of Valsalva, the sinotubular junction, the largest segment of the ascending aorta, the arch proximal to the origin of the left subclavian artery, the largest segment of the descending aorta, and the diaphragmatic hiatus (Fig. 1). Reference normal diameter values used in clinical practice at our institution are listed in Table 1. It has been demonstrated that indexing aortic size to body habitus yields a more accurate evaluation of patients at risk for thoracic aortic pathology, and many imagers may choose to include indexed sizes in their reports [6]. CT is the most commonly used imaging modality to evaluate thoracic aortic sizes as cardiac ultrasound is limited in its ability to visualize the arch and descending aorta and MR angiography is less widely available, more time-consuming, and potentially limited by implanted devices.

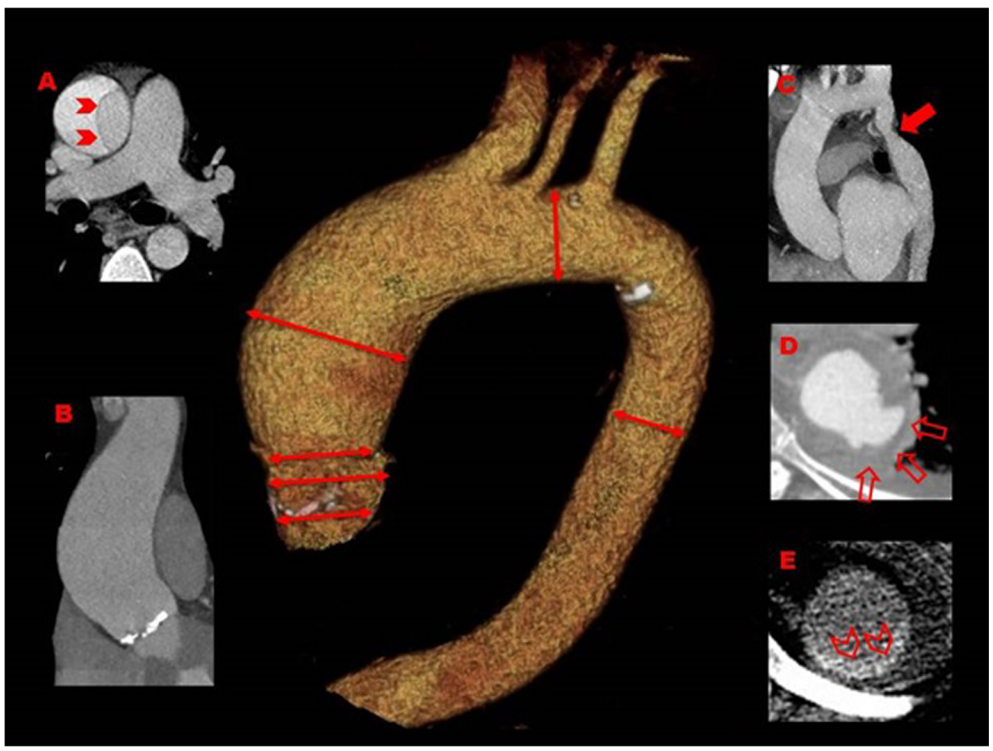

Fig. 1. Standard sites of thoracic aortic measurement demonstrated on 3D volume rendered image of thoracic aorta include (from proximal to distal): annulus, sinuses of Valsalva, sinotubular junction, ascending aorta, arch proximal to left subclavian artery, and descending aorta. Representative CT images of thoracic aortic pathology include **a** ascending aortic dissection with intimal flap (*closed arrowheads*), **b** ascending aortic aneurysm, **c** aortic coarctation (*closed arrow*), **d** penetrating aortic ulcer (*open arrows*), and **e** intramural hematoma (*open arrowheads*).

Table 1. Normal adult thoracic aortic diameters derived from transthoracic echocardiography and computed tomography measurements [2•, 46–48]

	Range of reported mean diameter (cm)	Reported standard deviation (cm)
Annulus	2.3 to 2.6	0.2 to 0.3
Sinuses of Valsalva	3.0 to 3.4	0.3
Sinotubular junction	2.6 to 2.9	0.3
Proximal ascending aorta	2.6 to 3.1	0.3 to 0.4
Mid-descending aorta	2.0 to 3.0	0.2 to 0.3
Diaphragmatic descending aorta	2.4 to 2.7	0.3 to 0.4

Technical considerations

Thoracic aortic CT angiography is widely performed using multidetector-row CT which allows for more rapid scan acquisition and greater scan area coverage as well as improved spatial and temporal resolution as compared to earlier single-detector CT. Thoracic aortic CT angiography protocols typically involve a non-contrast scan, an arterial phase scan, and in some cases delayed images. Non-contrast images are helpful in the evaluation of calcification and certain diagnoses such as intramural hematoma, while arterial and venous delayed images allow for complete vascular characterization. Bolus tracking software with a region of interest over the ascending aorta or a fixed arterial delay of 40 s can be used for timing of the arterial phase scan. Image acquisition with submillimeter slice thickness occurs during a single breath-hold at end-inspiration [7•]. As the aorta is a curved and geometrically complex organ, measurements of diameter at the standard locations described above should be obtained in double oblique short axis views using image post-processing software for optimal accuracy and reproducibility. At our institution, a consensus has been reached with input from radiologists, cardiologists, and cardiothoracic surgeons to perform aortic measurements from outer wall to outer wall of the vessel due to the importance of wall stress in pathogenesis of aortic disease. Cardiac ultrasound, in contrast, typically measures from leading edge to leading edge, which may account for some of the well-documented discrepancies between ultrasound and CT measurements, with CT generally yielding larger sizes [2•].

ECG-gated CT acquisition is a newer technique that allows significantly more accurate measurement of the aortic annulus, sinuses of Valsalva, and proximal ascending aorta by eliminating artifact related to cardiac motion. Motion artifact in these regions on non-ECG-gated acquisitions can make measurement difficult and also lead to artifact that can be mistaken for pathology by less experienced readers. When aortic root disease is suspected, ECG-gated acquisitions are preferable due to more reliable characterization of pathology and potential evaluation of spatial relationship to the coronary artery origins. ECG-gated images can be acquired during end systole or end diastole, which are the periods of the cardiac cycle with the least cardiac motion. Choice of systolic or diastolic acquisition is based on scanner capability as well as

individual patient evaluation including consideration of heart rate and eligibility for medications. High-pitch helical acquisition is an alternative technique to eliminate cardiac motion at the aortic root and has the additional benefit of reduced radiation dose exposure. An additional potential advantage of ECG-gated acquisition is the ability to perform preoperative evaluation of the entire coronary arterial system, thus potentially saving the patient from additional diagnostic studies such as invasive coronary angiography. It is important to note, however, that ECG-gated CT acquisition for simultaneous evaluation of the aorta and coronary arteries is a significantly more detailed process than evaluation of the aorta alone due to the need for careful patient evaluation, administration of medications, and complex image reconstruction and post-processing.

Drawbacks of using CT to evaluate the thoracic aorta include exposure of the patient to ionizing radiation and intravenous iodinated contrast. Total radiation dose exposure can be significantly reduced by techniques including prospective ECG triggering, selection of lower tube potential, automatic tube current modulation, limiting *z*-axis coverage, and use of iterative reconstruction algorithms [8]. Selection of lower tube potential has the added benefit of increasing the conspicuity of contrast due to increased photoelectric effect when kVp is lowered. The potential risk of nephrotoxicity from exposure to iodinated contrast media, already significantly lower than in the past due to the introduction of low and iso-osmolar contrast agents, can be further mitigated by patient hydration and selection of the minimum necessary quantity of contrast.

Thoracic aortic aneurysm

Thoracic aortic aneurysm (TAA) is often asymptomatic and detected incidentally when patients undergo other imaging studies such as chest radiography or cardiac ultrasound and are subsequently referred for CT evaluation. True arterial aneurysms are defined as vessel dilatation of greater than 50 % of normal diameter contained by all three intrinsic layers of the vessel wall (intima, media, and adventitia). False aneurysm, or pseudoaneurysm, is covered by less than three layers of the vessel wall and is most commonly secondary to trauma. True thoracic aortic aneurysm is commonly found clinically in association with aortic valve disease, atherosclerosis, in association with bicuspid aortic valve, and with genetic disorders such as Marfan's, Loeys-Dietz, and Ehlers-Danlos syndromes [9]. Specific genetic foci of susceptibility to thoracic aortic aneurysm are areas of emerging research [10]. True aneurysms are typically fusiform while false aneurysms are often saccular. TAAs tend to grow slowly over time; however, after crossing a certain threshold in size, typically 6 cm in size for the ascending aorta, the risk of acute pathology including dissection rises significantly [11]. As a significant minority of patients have already experienced dangerous complications by this size, the threshold for considering elective repair is lower than 6 cm but is variable in clinical practice. Current guidelines for elective ascending thoracic aortic aneurysm repair are complex and include thresholds of evaluation of 5.5 cm in asymptomatic patients, 4 to 5 cm in genetic syndromes, and 4.5 cm in patients undergoing aortic valve repair [2•]. Aneurysm growth rate of >0.5 cm per year in asymptomatic patients is an additional criterion for repair evaluation. In current clinical practice, patients

with ascending TAA are evaluated on an individual basis for elective aneurysm repair based on aortic size indexed to body habitus, presence of known aortopathy or genetic syndrome, and comorbidities contributing to surgical risk [12].

Although the precise upper limit of normal for size varies with patient age, gender, and size, one commonly used value in clinical practice is 4 cm [13]. At some institutions including our own, a more conservative threshold of 3.8 cm is used to determine which patients need ongoing imaging surveillance (Table 2). Care should be taken to perform measurements in double oblique short axis to avoid over- or underestimation of size due to oblique or rotatory course of the aorta. Growth over time is essential to document, and as yearly changes can be subtle, clinically significant growth can be much more apparent when compared to the earliest available scan rather than only to the most recently available [2•]. The most important points to be characterized in the CT evaluation of TAA include maximal aortic diameter, longitudinal extent of the aneurysm, involvement of the aortic valve and arch vessel, presence of periaortic hematoma or other findings suggesting leakage, and confirming the absence of aortic dissection [7•]. It is important to note that thoracic aortic dissection can occur in patients with genetic disorders such as Marfan's, Loeys-Dietz, and Ehlers-Danlos syndromes at normal aortic diameters, and these patients are therefore monitored over time with serial imaging for evidence of change in size and morphology rather than using absolute diameter threshold [11]. In addition, patients with these disorders who present with thoraco-abdominal aortic dissection are in some instances treated with complete graft repair and visceral

Table 2. Suggested clinical imaging evaluation and surveillance

Diagnosis	Evaluation	Surveillance	Alternatives
Thoracic aortic aneurysm	CT angiogram (CTA) chest/abdomen/pelvis (threshold for initiating ongoing surveillance >3.8 cm)	Annual CTA	• Annual MR angiogram (MRA) if young age or valvular pathology • Annual cardiac ultrasound if valvular pathology
Thoracic aortic repair (open or endovascular)	Post-procedural CT angiogram	Annual CTA with evaluation of repair dimensions, graft positions, and endoleak	Annual MRA for open repair; MRA of limited utility in stent-graft evaluation
Suspected acute aortic syndrome	Immediate CTA with non-contrast, arterial phase, and delayed images	Minimum annual CTA if medical management	More frequent surveillance intervals in high-risk patients
Bicuspid aortic valve with aortopathy	ECG-gated CTA of heart and thoracic aorta	Per clinical discretion; annual CTA or MRA if associated TAA and aortopathy	Periodic cardiac MRI or cardiac ultrasound if valvular stenosis or regurgitation
Aortic coarctation	CT angiogram or MR angiogram	Noninvasive pressure gradient studies followed by CT angiogram as indicated	• Annual MR angiogram (MRA) if young age • If stented, CTA for surveillance

artery reconstruction even when not all aortic segments are dilated in order to avoid future intervention [14].

Thoracic acute aortic syndromes

Acute aortic syndrome (AAS) describes a spectrum of aortic pathology that includes acute dissection, intramural hematoma, and penetrating aortic ulcer. Importantly, the imaging findings of AAS can overlap [15]. It is essential for treating clinicians to include thoracic AAS in the differential of patients presenting emergently with sharp or tearing chest pain and associated findings such as hypertension, asymmetric pulses, or symptoms of end-organ ischemia. CT angiography allows rapid characterization of AAS and triage for appropriate management.

Dissection

Thoracic aortic dissection is characterized by disruption of the intimal and often medial layers, which may or may not be apparent by imaging. This results in blood flow into the aortic wall from the true aortic lumen and the formation of a false lumen between the layers of the aortic wall. The Stanford classification is commonly used in clinical practice, with type A dissections involving the ascending aorta and type B dissections involving the descending aorta. Implications for management are that type A dissections generally require surgery while most type B dissections can be managed medically with hypertensive control and ongoing imaging to assess stability [16•]. Thoracic aortic dissection can be associated with high patient morbidity and mortality due to compromise of the coronary or cerebral circulation.

CT is the fastest and most widely available modality to evaluate for aortic dissection. Initial non-contrast images can demonstrate displacement of intimal calcification into the lumen, while contrast-enhanced images can define the intimal flap. It is important for the interpreting physician to characterize the true and false lumens as well as identify whether large branch vessels are arising from the true or false lumen to help predict end-organ ischemia, which is correlated with prognosis [17]. In cases where there is significant compression or compromise of the true lumen, a patient who would otherwise be managed medically may become a surgical candidate. It has been demonstrated that a widely patent false lumen with large entry tear may be correlated with worse outcomes [18]. Other essential complications associated with dissection that affect prognosis and must be identified include involvement of the coronary arteries, extension into the pericardium as identified by high-density pericardial effusion, rupture into the mediastinum, and involvement of the carotid arteries [19]. Additional potential complications include cardiac tamponade and acute aortic valve insufficiency which can be assessed via retrospectively ECG-gated studies when appropriate.

Intramural hematoma

Intramural hematoma (IMH) is a less common presentation of acute aortic syndrome in which there is bleeding into the aortic wall without frank blood flow communicating from the aortic lumen. Historically, IMH has been

thought to result from hemorrhage of the vasa vasorum into the aortic wall, although this has not been clearly established. IMH appears on CT as a crescentic high-attenuation rim along the aorta which does not enhance after the administration of contrast [20]. Non-contrast images are important for the identification of IMH which may be otherwise difficult to distinguish from opacified lumen or focal small dissection. Acute ascending aortic IMH is generally treated with the same interventions as ascending aortic dissection and demonstrates similar mortality and outcomes [21]. Clinically, IMH is followed over time to evaluate for extension, aortic remodeling, aneurysm formation, or evolution to frank aortic dissection [22].

Penetrating aortic ulcer

Penetrating aortic ulcers (PAU) result from focal ulceration of an existing atherosclerotic plaque into the medial layer of the aortic wall. Unlike IMH and dissection, PAU is not associated with hypertension or genetic wall abnormalities, but rather traditional atherosclerotic disease. On CT, PAU appears as a focal *crater-like* outpouching of the aortic wall in the region of an atherosclerotic plaque, often with irregular contour and margins [7•]. PAU can be differentiated from traumatic pseudoaneurysm by the absence of history of trauma and direct association with an atherosclerotic plaque. The differentiation of penetrating aortic ulcer from typical atherosclerotic disease is important as PAU can progress to aneurysm formation, rupture into the mediastinum, or dissection [23].

Post-repair considerations

Surgical techniques for repair of thoracic aortic aneurysm or acute aortic syndromes have advanced in recent years to include open graft repair and endovascular stent-graft repair [24]. Imaging can be performed in both the immediate post-procedural setting and on an ongoing surveillance basis to evaluate for post-procedural complications. Ascending aortic pathology in current clinical practice is treated with open graft repair, which may encompass the aortic root and ascending aorta only or include hemiarch repair. Investigation into the feasibility of endovascular repair of ascending aortic pathology is ongoing [25, 26•]. Low CT attenuation periaortic fluid collections are common in the immediate postoperative period for open graft repairs, but the presence of high CT attenuation (suggestive of blood), enlargement of the collection over time, or signs of superinfection should be carefully excluded. Non-contrast images can be particularly helpful in determining where the high-attenuation graft material begins and ends. ECG-gated examinations are of additional utility in ascending aortic repair evaluation to avoid potential misidentification of motion artifact for periaortic collection.

For descending aortic pathology, the choice between open and endovascular repair is based on comprehensive imaging and clinical evaluation of the patient with attention to age and comorbidities, as mortality rates from these interventions increase with advancing age [16•]. Thoracic stent grafts are thought to have a durability of approximately 10 years, making them a more appealing option for repair in older patients but less appropriate for young patients with trauma-related thoracic aortic pathology. Aortic characteristics including

extensive angulation and calcification at the graft placement site can affect graft prognosis [27]. When descending thoracic or thoraco-abdominal aortic aneurysms are treated with endovascular stent-graft repair, ongoing CT angiography surveillance is generally performed on an annual basis, although this may vary with surgeon preference. Key findings for the interpreting physician to evaluate include graft migration, stent fracture or dehiscence, and endoleak, or leakage of contrast into the excluded aneurysm sac which can lead to continued sac growth over time and risk of rupture. Detection of endoleak can be enhanced with delayed venous phase images or use of dual-energy acquisition to detect iodine within the excluded sac [28]. If identified early, reintervention using endovascular techniques including cuff placement or coiling is an increasingly utilized option. In a recent retrospective study of 680 patients who underwent thoracic aortic endovascular repair, 11.7 % required reintervention, and early and mid-term survival results were similar to treated patients who had not required reintervention [29]. Long-term aortic remodeling of the descending aorta can also result and should be documented [30, 31].

Congenital anomalies

Congenital aortic anomalies are not uncommon and can be detected incidentally on imaging studies or when patients become symptomatic and are referred for cross-sectional imaging. CT angiography provides fast, reproducible characterization of the thoracic aorta and other potential associated anomalies of the pulmonary or systemic venous system [32, 33]. ECG gating is optimal to provide additional information regarding the aortic valve, coronary arteries, and cardiac chambers. In young patients for whom thoracic aortic pathology has previously been identified and well characterized, targeted MR angiography can be a reasonable alternative for ongoing surveillance to avoid increasing cumulative radiation exposure over time.

Aortic coarctation

Aortic coarctation is a focal narrowing of the thoracic or abdominal aorta, most commonly found in the thorax at the level of the aortic isthmus just distal to the left subclavian artery. Coarctation can be suspected clinically in patients with unexplained hypertension at a young age or asymmetric lower extremity pulses as compared to the upper extremities. Coarctation is often imaged with cardiac ultrasound or MR angiography; however, the multiplanar capabilities and excellent spatial and temporal resolution of CT angiography in conjunction with radiation dose reduction techniques have led to the increasing use of CT for evaluation, with the additional benefit of being less susceptible to artifact from body habitus or implanted devices [34]. CT angiography can define the minimum diameter of the coarctation as well as the longitudinal extent, which can help guide the choice of open graft repair or endovascular stenting [35]. CT is also useful for identifying potential associated anomalies of the pulmonary or systemic vasculature prior to procedural intervention including collateral vessels and bicuspid aortic valve [36]. After treatment, ongoing patient monitoring is typically performed with noninvasive stress pressure studies, with an abnormal result requiring repeat

cross-sectional imaging evaluation to exclude recurrent coarctation. Less commonly, aneurysms can form at or adjacent to the coarctation site, which may be related to underlying aortopathy [37].

Bicuspid aortic valve and aortopathy

Bicuspid aortic valve (BAV) is a common condition resulting from congenital fusion of two coronary cusps to yield a single opening commissure during systole. A genetic linkage of BAV has been demonstrated, and for this reason, first-degree relatives of patients with known BAV should be referred for screening [38]. BAV is associated with aortopathy that can result in aneurysms of the ascending aorta, most commonly in the tubular portion [39], and is also associated with aortic coarctation [40]. There is emerging evidence that certain configurations of BAV may be associated with higher rates of aortopathy [41, 42]. For this reason, if bicuspid aortic valve is incidentally detected at cardiac ultrasound and the ascending aorta and arch cannot be well visualized, subsequent cross-sectional thoracic aortic evaluation by MR or CT angiography would be appropriate. ECG-gated CT acquisition yields the additional benefit of evaluation of the coronary arteries and potentially also morphologic valve function. Aortic dilation in BAV patients is generally confined to the ascending aorta, unlike in patients with tricuspid valves in whom concurrent descending aortic dilation is often seen [43]. Despite aortic dilation often seen with BAV, the risk of acute aortic syndrome secondary to aortopathy associated with BAV remains low and decision for intervention must balance this with the morbidity and mortality risk of open surgery [44•]. In clinical practice, prophylactic ascending aortic repair is considered in BAV patients at a threshold of 5.0–5.5 cm; however, resection strategies should be individualized to the patient based on anatomic configuration and comorbidities and considered in conjunction with the evaluation of aortic valvular abnormalities [45].

Summary

CT angiography has emerged as a leading imaging modality for assessment of thoracic aortic pathology due to wide availability, rapid acquisition, reproducibility, superior spatial and temporal resolution, and capability for 3D image post-processing The drawbacks of CT include exposure to radiation and iodinated contrast media; however, recent strategies for dose reduction and contrast optimization can substantially mitigate these risks. In the emergent setting, CT can rapidly identify patients with diagnoses on the spectrum of acute aortic syndromes who can then be triaged appropriately for immediate management. CT also plays an important role in post-procedural surveillance of the thoracic aorta for early and late complications from open or endovascular repair. Incidentally detected thoracic aortic pathology on other imaging modalities such as thoracic aortic aneurysm can be thoroughly and definitely characterized and followed over time to aid decision making about elective intervention. Congenital thoracic aortic anomalies can also be characterized and associated pulmonary or systemic vascular

anomalies identified. The addition of ECG gating to CT angiography acquisition can provide additional information regarding the aortic root, coronary arteries, and other cardiac structures without motion artifact. Modern CT angiography is a powerful imaging tool with multiple applications in the evaluation and management of thoracic aortic pathology.

Compliance with Ethics Guidelines

Conflict of Interest

Nandini M. Meyersohn, Khristine Ghemigian, Michael D. Shapiro, and Shimoli V. Shah declare that they have competing interests.

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Human and Animal Rights and Informed Consent

This article does not contain any studies with human or animal subjects performed by any of the authors.

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