American College of Radiology
ACR Appropriateness Criteria®
Thoracic Aorta Interventional Planning and Follow-Up

Variant 1: **Planning for pre-thoracic endovascular repair (TEVAR) of thoracic aorta disease.**

Radiologic Procedure	Rating	Comments	RRL*
CTA chest abdomen pelvis with IV contrast	9	See references [10,11,24-26,38-54,56-58].	☢☢☢☢☢
CTA chest with IV contrast	7	This procedure is appropriate if pathology is contained to the thoracic aorta. See references [10,11,24-26,38-54,56-58].	☢☢☢
MRA chest abdomen pelvis with IV contrast	7	See references [10,36,39,60,61].	O
MRA chest with IV contrast	7	This procedure is appropriate if pathology is contained to the thoracic aorta. See references [10,36,39,60,61].	O
MRA chest abdomen pelvis without IV contrast	6	Use this procedure if contrast is contraindicated. See references [36,39,60].	O
MRA chest without IV contrast	6	This procedure is appropriate if pathology is contained to the thoracic aorta and if contrast is contraindicated. See references [36,39,60].	O
US duplex Doppler iliofemoral arteries	5	This procedure may be appropriate as an adjunctive for preoperative access site planning. See references [56,68].	O
Aortography chest abdomen pelvis	5	This procedure may be appropriate for diagnostic purposes when urgent intervention is required. See references [45,56,61,64].	☢☢☢☢
US echocardiography transesophageal	5	This procedure is useful as an adjunctive study or for urgent/intraoperative evaluation but does not provide complete evaluation of the thoracic aorta and its branch vessels. See references [54,59,61,65,66].	O
CT chest abdomen pelvis without IV contrast	4	This procedure may have utility in cases of suspected intramural hematoma, in situations where patients cannot receive iodinated contrast, and/or where MRI is contraindicated. See references [10,11,24-26,38-54,56-58].	☢☢☢☢
CT chest without IV contrast	4	This procedure may have utility in cases of suspected intramural hematoma, in situations where patients cannot receive iodinated contrast, and/or where MRI is contraindicated. See references [10,11,24-26,38-54,56-58].	☢☢☢
US echocardiography transthoracic resting	4	See references [54,59,61,65,66].	O
US intravascular aorta	4	This procedure may be useful as an adjunctive intraprocedural technique. See reference [67].	O
CT chest abdomen pelvis without and with IV contrast	3	See references [2-14,33,34,61,71-83].	☢☢☢☢
CT chest abdomen pelvis with IV contrast	3	CTA is the preferred examination. See references [2-14,33,34,61,71-83].	☢☢☢☢

CT chest without and with IV contrast	3	Use this procedure if contrast can be given. CTA is the preferred examination (CTA can include a noncontrast phase as per the ACR definition).	☢☢☢
CT chest with IV contrast	3	Use this procedure if contrast can be given. CTA is the preferred examination.	☢☢☢
FDG-PET/CT skull base to mid-thigh	3	See reference [70].	☢☢☢☢
X-ray chest	2	See references [59,69].	☢
Rating Scale: **1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate**			***Relative Radiation Level**

Variant 2: **Follow-up for post-thoracic endovascular repair (TEVAR) of thoracic aortic disease.**

Radiologic Procedure	Rating	Comments	RRL*
CTA chest abdomen pelvis with IV contrast	8	See references [12-14,33,34,61,71-83].	☢☢☢☢☢
CTA chest with IV contrast	8	This procedure is appropriate if pathology is contained to the thoracic aorta. See references [12-14,33,34,61,71-83].	☢☢☢
MRA chest abdomen pelvis with IV contrast	6	MR should primarily be considered if stent material allows for diagnostic MRI (eg, nitinol). See references [39,61,74,84,87-89].	O
MRA chest with IV contrast	6	This procedure should primarily be considered if stent material allows for diagnostic MRI (eg, nitinol) and if pathology is contained to the thoracic aorta. See references [39,61,74,84,87-89].	O
MRA chest abdomen pelvis without IV contrast	5	This procedure may be useful if stent is compatible and if contrast is contraindicated. See references [39,61,74,84,87-89].	O
MRA chest without IV contrast	5	This procedure may be useful if stent is compatible, if contrast is contraindicated, and if pathology is contained to the thoracic aorta. See references [39,61,74,84,87-89].	O
Aortography chest abdomen pelvis	5	This procedure is not for routine follow-up but may be useful if the source of endoleak is unclear on cross-sectional imaging. See reference [76].	☢☢☢☢
CT chest abdomen pelvis without IV contrast	4	This procedure may be useful for follow-up in stable patients, with addition of CTA if there is a change over time. See references [12-14,33,34,61,71-83,86].	☢☢☢☢
CT chest without IV contrast	4	This procedure may be useful for follow-up in stable patients in whom pathology is contained to the thoracic aorta, with addition of CTA if there is a change over time. See references [12-14,33,34,61,71-83,86].	☢☢☢
US echocardiography transesophageal	4	See references [61,84].	O
US echocardiography transthoracic resting	4	See references [61,84].	O
X-ray chest	4	This procedure may be helpful for assessment of stent migration and graft fracture. See references [38,71].	☢
CT chest abdomen pelvis without and with IV contrast	3	Use this procedure if contrast can be given. CTA is the preferred examination (CTA can include a noncontrast phase as per the ACR definition). See references [12-14,33,34,61,71-83].	☢☢☢☢
CT chest abdomen pelvis with IV contrast	3	CTA is the preferred examination. See references [12-14,33,34,61,71-83].	☢☢☢☢
CT chest without and with IV contrast	3	Use this procedure if contrast can be given. CTA is the preferred examination (CTA can include a noncontrast phase as per the ACR definition). See references [12-14,33,34,61,71-83].	☢☢☢

CT chest with IV contrast	3	Use this procedure if contrast can be given. CTA is the preferred examination.	☢☢☢
US duplex Doppler aorta abdomen	2	This procedure will provide useful information only for the abdominal portion of the stent graft (if this applies to the patient) and cannot be reliably used in the chest, given the poor acoustic window. See references [38,90].	O
Rating Scale: **1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate**			***Relative Radiation Level**

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Summary of Literature Review

Introduction/Background

Since the first thoracic aorta endograft device was approved by the FDA in 2005, thoracic endovascular aortic repair (TEVAR) has undergone rapid evolution and is now applied to a range of aortic pathologies, including trauma, aneurysm, dissections, intramural hematoma (IMH), penetrating atherosclerotic ulcer (PAU), and even persistent congenital malformations such as aortic co-arctation [1,2]. TEVAR has also been used as a bridge treatment before open repair in patients with aortic infections who develop circulatory collapse or fistulization to adjacent structures [3,4]. Compared with open surgical repair, TEVAR has demonstrated favorable perioperative morbidity and mortality data for many forms of thoracic aorta pathology [5]. TEVAR also allows for intervention in patients with more extensive comorbidities that would otherwise preclude open surgical repair [6]. In certain patient groups, including variant anatomy such as aberrant right subclavian artery with aneurysmal degeneration of the vessel origin, hybrid open and endovascular procedures are performed wherein affected visceral branch vessels are surgically revascularized with concomitant or staged endovascular exclusion of the primary aortic pathology [7-9].

Thoracic aortic aneurysms are defined as permanent dilation of the thoracic aorta by more than 2 SDs over the mean. Based on population studies, the thoracic aorta is generally considered aneurysmal at 4 cm. Up to one-third of thoracic aortic aneurysms extend into the abdominal aorta, increasing complexity of endovascular or surgical repair [10]. Intervention is indicated when aneurysm diameter exceeds 5.5 cm or demonstrates rapid growth [10]. More conservative thresholds are implemented in patients with underlying connective tissue disorders or a bicuspid aortic valve.

Acute aortic syndromes, broadly defined as a disease spectrum encompassing PAU, IMH, and aortic dissection, may be treated with conservative medical therapy or surgical or endovascular intervention, depending on the presentation. The goal of endovascular stent grafting in these conditions is to maintain true lumen patency, prevent aneurysmal degeneration, and, in the case of dissection, seal intimal tears and induce thrombosis in the false lumen [11]. When clinically suspected, acute aortic syndrome requires immediate diagnostic evaluation to exclude an impending vascular catastrophe. Indications for surgical intervention in these conditions include lack of symptomatic improvement with medical therapy, resistant hypertension, rapid expansion of IMH or false lumen, and concern for impending rupture [5,12-15]. It has been shown that nearly 50% of acute aortic syndrome patients will develop a recurrent acute aortic event within 1 to 2 years of initial presentation, underscoring the need for close follow-up in this population [16].

With the exception of trauma, the vast majority of aortic pathologies arise in patients aged 60 to 80 years. Risk factors include male gender, long-standing hypertension, hyperlipidemia, arteriosclerosis, and smoking [17]. However, there are a variety of genetic syndromes and single-gene mutation conditions that confer a higher risk of thoracic aortic aneurysm and dissection in younger patients, including Marfan syndrome (associated with *FBN1* mutations), Loeys-Dietz syndrome (associated with *TGFB* and *SMAD* mutations), and familial thoracic aorta aneurysm leading to aortic dissections (associated with *ACTA2* mutations) [18]. Even when syndromes are not suspected, patients with a bicuspid aortic valve or a strong family history of aortic disease have higher risk of

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developing aneurysmal disease of the thoracic aorta [19,20]. Inflammatory vasculitides such as Behçet disease and Takayasu arteritis may result in arterial stenoses, aortic pseudo-aneurysm, and anastomotic dehiscence in cases of prior surgical repair, all of which have been effectively treated with TEVAR [21-23]. Clinicians encountering patients with known or suspected genetic risk factors or inflammatory vasculitides should have a high suspicion for acute aortic pathology in the appropriate clinical scenario, as well as a low threshold for imaging.

Regardless of the pathology at play, the TEVAR procedure is similar. Access in TEVAR procedures is increasingly obtained percutaneously via the common femoral artery, although femoral artery cutdowns are still performed in up to 20% of cases. Although obesity was once considered a relative contraindication to percutaneous access, recent literature has demonstrated that it does not affect procedural success rates in the hands of an experienced surgeon or interventionalist [24]. The most important factor in percutaneous vessel selection appears to be vessel diameter, with common femoral artery diameters >8 to 9 mm exhibiting lower rates of complication [25,26].

Careful attention to preoperative imaging is then paid to the involved landing zones of the thoracic aorta. Proximal and distal landing zones should ideally be 2 to 3 cm in length to ensure an adequate seal and decreased rates of endoleaks, aneurysmal degeneration, and device migration [27]. When the proximal landing zone approaches the aortic arch vessels, the possibility of the stent graft occluding a vessel ostium arises. In such cases, vascular bypass or a staged or hybrid approach may be necessary to ensure patency. If aortic pathology extends into the abdominal aorta, care must be taken to assess for possible stent coverage of major branch vessels; when this situation arises, more involved repairs are necessary.

Despite the promise of TEVAR, it must be emphasized that the procedure is technically complex and has significant perioperative mortality of up to 12.5%, as reported in one series examining thoracoabdominal aneurysm endograft repair [28]. Frequent intraoperative complications include damage of the target vessel and its branches, device malposition, and access problems. Significant perioperative complications abound, including stroke, persistent renal dysfunction, and paraplegia or paraparesis secondary to spinal cord ischemia. [7,29]. Because late endoleaks have been reported in 10% to 41% of cases, continuous surveillance imaging is necessary to gauge the need for reintervention [30]. Additional postoperative complications include progressive aneurysmal degeneration of the aorta as well as potentially life-threatening complications such as retrograde dissection [31].

A commonly cited disadvantage of TEVAR with respect to open repair is the high rate of reintervention. For example, a recent study demonstrated a 32% reintervention rate at 4.7 years after aortic dissection repair [32]. A caveat is that the presence of an existing endograft can reduce operative risk in subsequent procedures. In cases of distal aneurysmal degeneration in the setting of prior TEVAR for chronic type B dissection, the indwelling endograft can serve as the attachment point for a new aortic graft, thereby reducing the extent and risk associated with reintervention [33].

Open surgical repair remains the treatment of choice in cases of acute Stanford type A dissection. This is because of the myriad anatomic constraints imposed by the proximity to the coronary ostia, aortic root or valve, and brachiocephalic trunk [11]. Use of TEVAR in asymptomatic, uncomplicated, chronic Stanford type B dissection is also controversial, with mixed survival benefit results when comparing TEVAR with optimized medical therapy [34,35]. Relative contraindications to TEVAR include inadequate proximal or distal seal zones, aortic size discrepancies with respect to manufacturer guidelines, inadequate access, and extensive circumferential thrombus or atheroma at the desired landing zones [27].

Imaging plays a vital role in the pre- and postintervention assessment of TEVAR patients. Accurate characterization of pathology and evaluation for high-risk anatomic features are necessary in the planning phase, whereas careful assessment for graft stability, aortic lumen diameter, and presence of endoleak are paramount in the follow-up period. Because imaging studies carry inherent risk, careful attention must be paid to utilize the most efficacious study that will limit morbidity to the patient while identifying important complications before they become problematic. One finding that has become increasingly clear is that the thoracic aorta demonstrates dynamic changes after TEVAR. As the natural history of post-TEVAR patients evolves, the importance of these gradual changes will become clearer. For example, up to 73% of patients undergoing repair of acute type B aortic dissection will show aortic growth or new aneurysm at 5 years after TEVAR [14]. Although reintervention is not necessary in all cases, close follow-up is mandatory given the propensity for dynamic vascular changes over time. Therefore, TEVAR should be thought of more as a chronic management tool than as definitive intervention.

Overview of Imaging Modalities

A variety of imaging modalities are available for the evaluation and follow-up of thoracic aortic pathology. Advances in imaging technology over the past 2 decades have greatly expanded the role of noninvasive cross-sectional imaging in the pre- and postintervention periods. Computed tomography angiography (CTA) and, to a slightly lesser extent, magnetic resonance angiography (MRA) are now the preferred modalities in the assessment of the thoracic aorta given superior anatomic accuracy, capacity to discern relevant complications, and ability to infer dynamic vascular information [36]. Catheter angiography has largely been replaced by CTA and MRA for diagnostic evaluation but remains a useful tool in cases where acute intervention is required. Ultrasound (US), echocardiography, radiography, and select nuclear medicine studies currently play an adjunctive role in the evaluation and follow-up of thoracic aortic disease and are principally utilized to answer specific anatomic and prognostic questions. A variety of factors contributes to the appropriateness of each imaging study, including acuity of the pathologic process, planned intervention, patient age, medical comorbidities, and endograft composition.

For the purposes of distinguishing between CT and CTA, ACR AC topics use the definition in the Practice Parameter for the Performance and Interpretation of Body Computed Tomography Angiography (CTA) [37]:

> "C*TA uses a thin-section CT acquisition that is timed to coincide with peak arterial or venous enhancement. The resultant volumetric dataset is interpreted using primary transverse reconstructions as well as multiplanar reformations and 3D renderings."*

All elements are essential: 1) timing, 2) reconstructions/reformats, and 3) 3-D renderings. Standard CTs with contrast also include timing issues and reconstructions/reformats. Only in CTA, however, is 3-D rendering a **required** element. This corresponds to the definitions that the Centers for Medicare & Medicaid Services has applied to the Current Procedural Terminology codes.

Discussion of Procedures by Variant

Variant 1: Planning for pre-thoracic endovascular repair (TEVAR) of thoracic aorta disease.

CTA

Multidetector CT is the imaging modality of choice for preoperative assessment before TEVAR because of short scan times and superior spatial and temporal resolution [38,39]. CTA is unmatched in its ability to provide isotropic data as well as robust and homogeneous intraluminal contrast enhancement [36]. In cases of proximal thoracic aorta pathology, electrocardiography (ECG) gating can help achieve motion-free images along with ideal contrast enhancement. Acquisition of thin-section (0.5 to 2.0 mm) axial images with subsequent reconstruction of multiplanar reformats, maximum-intensity projections, curved planar reformats, and volume-rendered images allows for precise assessment of aortic anatomy [10,26]. Centerline or double oblique measurements are critical to avoid errors based on aortic obliquity; such measurements are easily obtained with modern postprocessing software [40]. More advanced postprocessing techniques such as 3-D virtual angioscopy, which affords a virtual endoluminal view, have shown utility in the surgical planning period [41]. Because thoracic aorta pathology often extends to involve the abdominal aorta, imaging of the chest, abdomen, and pelvis is standard in evaluation of vascular pathology.

CTA can also identify higher-risk features and findings that may predict higher rates of postintervention complications. For example, it has been shown that increasing aortic tortuosity, which can be expressed as index values based on CTA measurements, is associated with increased risk of endoleak, stroke, and reduced survival after TEVAR for thoracic aortic aneurysm [42,43]. In patients with acute aortic dissection, the presence of a single entry, as opposed to multiple sites, is associated with higher aortic growth rates, possibly because of deranged inflow and outflow dynamics; CTA has been shown to reliably detect entry tears with 82% sensitivity and 100% specificity [44]. When abdominal visceral branches are involved and there is potential for celiac trunk or superior mesenteric artery coverage by the stent graft, CTA can help determine the presence of collateral vessels [45]. In the absence of collaterals, an open surgical or hybrid approach may be necessary to avoid visceral ischemia.

CTA may also be able to guide device selection. One complication after TEVAR is the development of a bird-beak endograft configuration in the proximal landing zone, which portends a higher risk of endoleak. This configuration results most commonly when the proximal landing zone sits within a highly curved or angulated

aortic arch [46]. Specially designed endografts that are less susceptible to these morphologic changes can therefore be selected when preoperative imaging identifies problematic anatomy.

An important subset of TEVAR is its use in repair of pathologies involving the aortic arch. A detailed understanding of the spatial relationship of the arch vessels and the luminal changes throughout the diseased arch is required for proper patient and device selection [47]. Minimum proximal and distal landing-zone intervals are necessary, with reported values in the literature ranging from 20 to >50 mm [25,48]. When the proximal landing zone approaches or overlaps the origin of the left subclavian artery, there is an increased possibility of endoleak; in such cases, embolization of the artery or vascular bypass may be considered. Several commercially available devices require a normal-caliber proximal aorta with narrow acceptable landing-zone diameter ranges; for example, a recently approved multibranch endograft system requires a proximal aortic landing-zone diameter between 24 and 30 mm, thereby severely limiting the potential patient population [49,50]. Endograft sizing is of critical importance because an undersized graft may lead to fixation and sealing compromise, with resultant type I endoleaks and graft migration. It must be anticipated that most aortas increase in diameter over time as a result of age-related change and progression of aneurysmal disease in affected patients [51].

Although open repair is traditionally pursued for proximal aorta pathology, endovascular stent grafting is possible in certain cases of type A dissection and proximal thoracic aortic aneurysm. A 2011 study demonstrated a 98% technical success rate for TEVAR in the treatment of 45 patients with type A dissection in which the entry tear was at least 2.5 cm from the coronary ostia [52]. Notably, transposition of the supra-aortic vessels was necessary in nearly half of the patients in this study to ensure an adequate landing zone. Other authors recommend a minimum distance of 1 cm from the intimal tear entry site to the sinotubular junction and brachiocephalic trunk [11]. CTA is essential in planning for these cases to avert compromise of coronary and brachiocephalic circulation as well as aortic valve dysfunction.

An essential aspect of pre-TEVAR planning is evaluation of the iliofemoral vasculature. Thoracic aorta endografts tend to be larger than their abdominal counterparts, requiring insertion sheaths with outer diameters up to 27 French. For this reason, a minimum vessel diameter of at least 8 to 9 mm is preferred [25,26]. Additionally, increased vessel depth, degree of femoral artery calcification, and iliofemoral tortuosity have been shown to be negative predictors of percutaneous TEVAR success [24]. All of these variables are readily evaluable with CTA and, in conjunction with sound clinical judgment, can be used to avoid the dreaded complication of iliac disruption necessitating open surgical repair. In cases of unfavorable anatomy, surgical or endovascular conduits have been shown to reliably facilitate endovascular repair [53].

The radiation dose associated with properly performed CT examinations in the evaluation of thoracic aortic disease is not of significant concern [54]. Potential nephrotoxicity from iodinated contrast in patients with impaired renal function is the primary concern in this patient population, although the benefits of obtaining key diagnostic information typically outweigh the low risk of developing contrast-induced nephropathy [55]. Utilization of modern CT optimization techniques, such as high-pitch spiral CT imaging, low kilovolt (peak) imaging, wide-area detectors, and iterative reconstruction techniques, allows for lower volumes of contrast and lower radiation dose with adequate diagnostic image quality [39,56,57].

CT

Unenhanced CT is useful for identification of aortic size, acute IMH, and aortic calcification. In conjunction with CTA, sensitivity for detection of IMH is as high as 96%, and sensitivity and specificity for detection of the intimal flap in aortic dissection approach 100% [11,39]. Moreover, unenhanced CT can delineate complications related to acute aortic syndromes such as mediastinal or pericardial hemorrhage and rupture. The addition of CTA allows for comprehensive assessment of other sequelae, including end-organ ischemia, acute aortic valvular insufficiency, intravascular thrombus, and supra-aortic, coronary, and mesenteric vascular involvement [25,39,58].

The use of contrast-enhanced CT and multiphase CT (without and with contrast) can provide similar information to CTA with regard to the anatomic extent of vascular pathology. Often, such studies are pursued to investigate other clinical questions or vague presentations and incidentally reveal significant vascular findings in the thoracic aorta. The lack of standard thin-section image acquisition, arterial-phase bolus timing, and 3-D renderings with these techniques is the principal limitation, and therefore CTA is the preferred imaging modality for the dedicated workup of thoracic aorta diseases [37,39].

MRA

Similar to CT, magnetic resonance imaging (MRI) of the thoracic aorta can be performed with and without intravenous contrast. The principle advantage of MRI over CT is the lack of ionizing radiation, making it a particularly attractive imaging option in young patients. MRI is a more time-consuming study than CT, necessitating a stable patient. Importantly, MRI confers similar sensitivity and specificity as CTA and transesophageal echocardiography (TEE) for detection of dissection flaps, although like TEE it is less accurate for detection of branch vessel involvement [59].

There are a variety of unenhanced MRA techniques, including time of flight, phase-contrast imaging, ECG-gated fast spin-echo, and steady-state free precession (SSFP). SSFP, for example, has been shown to have equal accuracy for the assessment of aortic diameter compared with contrast-enhanced MRA (CE-MRA) [60]. The SSFP technique is also useful for visualization of dissection flaps [39]. General limitations with unenhanced MRA include loss of signal due to turbulent flow, long acquisition times, susceptibility to field inhomogeneity and motion, and the need for considerable patient cooperation for sequences requiring breath holding [36].

CE-MRA using 3-D spoiled gradient-echo sequences is the preferred MRI technique for thoracic aortic imaging, providing superior arterial signal, high spatial and contrast resolution, and rapid data acquisition during a single breath hold [36,39]. ECG gating may be added for motion-free evaluation of the ascending aorta and aortic root. Similar to the typical multiphasic CTA protocol, CE-MRA studies generally consist of unenhanced, arterial, and delayed-phase images. Various triggering methods can be used to ensure adequate gadolinium contrast opacification. Because the images are acquired in a near-isotropic fashion, similar multiplanar reformats to those used in CTA can be produced [39]. In addition to characterizing the extent of aortic pathology and providing precise, highly reproducible aortic measurements, CE-MRA has particular efficacy in delineation of mural thrombus versus intramural blood when CT results are equivocal [10,61]. It is also useful in the differentiation of aortic wall inflammation from intramural hemorrhage and atheroma [36]. A point of caution in the interpretation of MRA is to use source images for measurements, as maximum-intenstiy projection images may obscure the vessel wall and lead to underestimation of lumen size [10].

More advanced magnetic resonance (MR) applications allow flow mapping via time-resolved imaging techniques. Such techniques allow for the evaluation of abnormal vascular anatomy, atherosclerotic plaque burden, collateral blood flow, and hemodynamic parameters in the involved segment of aorta [36,39].

Although CE-MRA is preferred for the aforementioned reasons, certain situations exist in which unenhanced MRA is desirable. These include patients with poor intravenous access; advanced, dialysis-dependent renal failure with glomerular filtration rate <30 mL/min/1.73 m^2 (because of the risk of nephrogenic systemic fibrosis); and pregnancy (because of the possible teratogenic effects of gadolinium-based contrast agents) [55,60,62].

Aortography

Catheter angiography has largely been replaced by cross-sectional imaging in the evaluation of patients with suspected aortic pathology. An exception is in cases of coexisting malperfusion involving the coronary, visceral, or cerebral circulations. In such cases, angiography allows for evaluation and possible revascularization of the affected vascular bed along with further characterization of aortic pathology [45,61,63]. Angiography has gained traction in the hybrid operating-room approach to acute type A aortic dissection, in which diagnostic and interventional angiography techniques are combined with open surgical repair [63]. Catheter angiography allows for assessment of luminal size of the iliofemoral system but is limited in its ability to assess for atherosclerotic plaque burden [56]. Additionally, digital subtraction angiography remains the gold standard for preintervention visualization of the artery of Adamkiewicz, an important consideration when there is high concern for spinal cord ischemia [64].

TEE and TTE

In hemodynamically unstable patients, transthoracic echocardiography (TTE) is a useful imaging study for rapid evaluation of valvular function, aortic root dilation, and thoracic aortic dissection. This can be further supplemented with TEE, which allows for comparatively superior anatomic evaluation and can be left in place for intraoperative monitoring [61,65]. Although offering comparable sensitivities to CT and MRI for detection of thoracic aortic dissection, TEE is limited in its sensitivity for detection of branch vessel involvement and delineation of pathology below the gastroesophageal junction [59]. Echocardiography can also evaluate for concomitant cardiovascular disease and identify patients in whom coronary revascularization or valvular repair may be indicated [54,66].

IVUS
Similar to intraprocedural TEE, intravascular US (IVUS) is an additional adjunctive imaging tool that can aid in optimal visualization of intimal tears, ideal endograft positioning, assessment of branch vessel patency, and detection of abnormal flow within the false lumen and excluded aneurysm sac after endograft placement [67].

US
In cases where thoracic aortic disease does not extend into the abdomen and no cross-sectional imaging of the iliofemoral system is available, US duplex Doppler of the iliofemoral arteries is useful for assessing adequate access. US duplex Doppler allows for assessment of vessel diameter and plaque burden along the anterior aspect of the vessel. In one recent series examining the use of US-guided femoral access in abdominal aortic endovascular aneurysm repair patients, intraoperative US guidance was shown to significantly reduce operative time and access wound complications [68]. Although similar dedicated studies are not available for TEVAR, the underlying principle is directly transferrable. Similarly, IVUS at the time of intervention has been shown to provide reliable information regarding iliofemoral morphology and atherosclerotic disease burden [56].

Radiography
Chest radiographs will demonstrate abnormalities in a large percentage of patients with acute thoracic aorta pathology. For example, in patients presenting with acute aortic dissection, >80% demonstrated chest radiograph abnormalities, with mediastinal widening seen in just over 50% of cases [59,69]. However, radiography can only alert to an underlying abnormality and provides no specific information regarding type of pathology or detailed anatomic information necessary for interventional planning.

FDG-PET/CT
Nuclear medicine studies play a limited role in the workup of acute aortic pathology. In patients presenting with acute type B aortic dissection, greater uptake of fluorine-18-2-fluoro-2-deoxy-D-glucose (FDG) in the aortic wall as seen on positron emission tomography (PET)/CT has been shown to predict rupture and dissection propagation [70].

Variant 2: Follow-up for post–thoracic endovascular repair (TEVAR) of thoracic aortic disease.

CTA
CTA is the optimal modality for post-TEVAR imaging given its sensitivity for the detection of endoleaks, changes in aortic/aneurysm diameter, evaluation of false lumen thrombosis, and assessment for device migration and integrity [71]. As discussed previously, one of the limitations of TEVAR is the high rate of reintervention. Although reintervention rates are lower for aneurysmal disease, trauma, and IMH, routine surveillance imaging is requisite regardless of aortic pathology. Although there are no universally accepted guidelines, lifelong follow-up is recommended after TEVAR because endoleaks can develop at any time after intervention [72,73]. Routine postprocedure imaging protocols typically entail follow-up within 30 days of the procedure, at 3 to 12 months, and regular surveillance imaging at 6- to 12-month intervals thereafter depending on stability [61]. These intervals may gradually be lengthened if stability or improvement is documented over several examinations. Future directions for surveillance will almost certainly be individualized based on personal risk factors. In patients in whom no endoleak is observed, aneurysm sac size is shrinking, and proximal and distal seal zones are adequate, less frequent surveillance imaging can safely be pursued [74].

The optimal CTA protocol for TEVAR follow-up is not well defined. Most commonly a triphasic protocol is performed with acquisition of unenhanced, arterial, and delayed-phase (60-120 seconds after injection) imaging. The utility of the unenhanced phase is to differentiate extraluminal calcification or postendoleak intervention material from extraluminal contrast seen on contrast-enhanced images. Although comprehensive, such a protocol delivers a high radiation dose. Some institutions employ a late delayed phase of 300 seconds to better visualize low-flow endoleaks [72].

With regard to endoleak, type I endoleaks occurring at the proximal (Ia) or distal (Ib) landing zones are the most common cause for reintervention following TEVAR, occurring in up to 15% of cases [75]. In contrast to abdominal aorta endovascular repair where type II endoleaks are most common, type II endoleaks occur in a small percentage of TEVAR patients, likely because of fewer patent collateral vessels in the thorax compared with the abdomen [76]. Furthermore, type II endoleaks are not associated with increased risk of thoracic aorta rupture and are often managed conservatively. Types III, IV, and V endoleaks occur much less frequently, with type III being the only subtype other than type I to require immediate therapy [72].

It has been shown that luminal diameter as determined from 3-D measurements correlates well with aortic luminal area during the postoperative period and can be used as a proxy for luminal blood flow [77]. This applies to both true and false lumens in cases of dissection, although the relationship becomes less clear with large false lumen diameters because of the propensity for complex luminal configuration. Serial evaluation of true and false lumen diameters via CTA in the postintervention period is a marker for vascular remodeling. Recent midterm results from the VIRTUE Registry demonstrate similar rates of vascular remodeling in patients with uncomplicated acute and subacute type B dissections. Along with other studies demonstrating a mortality benefit in the treatment of subacute to chronic uncomplicated type B dissections, these data suggest that TEVAR is a viable alternative treatment option in the management of these patients compared with optimized medical therapy [12,33,34,78].

Partial false lumen thrombosis is an important predictor of regional luminal growth and reintervention rate. Although incompletely understood, this is postulated to be due to a regional increase in luminal pressure owing to small diameter [79]. Chronic dissections tend to show lesser degrees of remodeling, perhaps because of the frequent presence of multiple intimal tears and development of intercostal collaterals in these patients [14,80]. When there is a question of false lumen thrombosis status, the absence of contrast enhancement on arterial and early delayed-phase CTA does not necessarily indicate complete thrombosis given the possibility of a low-flow state. In such cases, more-delayed imaging demonstrates higher sensitivity for detection of partial thrombosis [81].

Similar to the findings seen in TEVAR for aortic dissection, there is significant vascular remodeling when TEVAR is used for IMH or PAU, with near-complete normalization of aortic diameter at 1 year as measured on CTA [13,82].

CTA is also the preferred imaging modality of choice for evaluation of endograft infection, one of the most serious complications after TEVAR. A recent study demonstrated that in the small number of patients with an infected endograft, CTA suggested the diagnosis in 78% of cases, with the most common findings being periaortic inflammation and erosion into surrounding structures [83].

The principle disadvantages of CTA in the follow-up period are potential nephrotoxicity and cumulative radiation dose, particularly in younger patients. A study evaluating radiation exposure during TEVAR and subsequent follow-up found that cumulative lifetime radiation exposure in these patients is likely to exceed 350 mSv, conferring an increased lifetime risk of at least 2.7% for developing solid-organ malignancy or leukemia [84]. The development of ever-advanced iterative reconstruction algorithms permits the use of lower tube energies, thereby allowing for reduced patient radiation exposure. A recent study highlighted radiation dose reductions ranging from 63% to 69% at standard kilovolt (peak) using a fully iterative reconstruction algorithm as compared with standard filtered back-projection without appreciable changes in conspicuity of endoleaks or in-stent thrombosis [85]. Dual-energy acquisition offers the possibility of eliminating the unenhanced phase via the creation of a virtual noncontrast image set. Another recent study demonstrated near-perfect correlation between single- and dual-phase dual-energy scans in comparison with a traditional three-phase protocol, with 19.5% and 64.1% less radiation exposure, respectively [72].

CT

Although not ideal given the inability to directly detect endoleaks, unenhanced CT can still offer valuable follow-up information in TEVAR patients with chronic renal insufficiency and stent grafts not amenable to MRA. Unenhanced CT is useful in the assessment of graft migration, aortic rupture, and delineation of vascular calcifications, hematoma, and surgical material that could otherwise be confused for endoleak on CTA examinations [36]. Additionally, by using aneurysm sac diameter as a proxy for graft and anastomotic integrity, unenhanced CT can indirectly suggest endoleak if sac volume increases over time by more than 2% [86]. In patients with stable findings on early postintervention imaging and a low risk of graft complications, follow-up with unenhanced CT complemented by CTA when questions arise may be a viable strategy.

Similar to the preprocedure discussion, non–vascular-dedicated contrast-enhanced CT and multiphase CT (without and with contrast) examinations may provide useful post-TEVAR information and alert the radiologist to complications but are suboptimal compared with CTA, given the lack of standard thin-section image acquisition, specific bolus timing, and 3-D renderings.

MRA

MRI after TEVAR suffers from severe susceptibility to artifacts relating to the stainless steel used in many stent graft types, obscuring surrounding relevant anatomy and limiting evaluation for endoleak [39,84]. One particular

group in which MRI is a preferred imaging modality is patients in whom nitinol stents are placed. This is because these endografts do not produce susceptibility artifacts, thereby allowing adequate visualization of the underlying vasculature [74]. Various studies have demonstrated comparable to superior sensitivities in detection of endoleak with MRA compared with CTA when such stents are used [87,88]. Additional research has shown that in patients with MR-compatible endografts, unenhanced MRA can reliably assess stent position and geometry, whereas CE-MRA can sufficiently evaluate endograft hemodynamics and aortic diameter [89].

A principal advantage of MRI in the follow-up period is its lack of ionizing radiation. In younger patients in whom cumulative radiation dose from repeat CT examinations is of particular concern, placement of an MR-compatible endograft should strongly be considered so that routine MRI surveillance can be obtained [61]. As noted previously, the use of CE-MRA is limited in cases of severe renal dysfunction and pregnancy.

Aortography

Given its invasiveness, catheter angiography is not a routine surveillance tool after TEVAR. However, in cases where significant endoleaks are identified on cross-sectional imaging or where the origin of endoleak is unclear, catheter angiography is indispensable for further anatomic characterization as well as definitive treatment [76].

TEE and TTE

In cases where the extent of residual aortopathy is confined to the aortic root or proximal aorta dilation, TTE may play an adjunctive surveillance role, reducing the frequency of CT or MR surveillance [61]. TEE provides suboptimal evaluation of suspected endoleak and should be considered only in patients in whom CTA is precluded because of severe renal dysfunction or contrast allergy [84].

US

US duplex Doppler is an alternative modality for follow-up of abdominal aortic endovascular aneurysm repair with high specificity for detection of endoleaks and high accuracy for evaluation of aneurysm sac size. The addition of contrast material makes US an even more sensitive and specific test than CTA for characterization of endoleaks [90]. Its use in TEVAR is impractical in the chest given poor acoustic windows but may provide diagnostic information for the abdominal aspect of the stent graft [38].

Radiography

Radiography in the postintervention period has traditionally been used to evaluate for stent migration and integrity [71]. However, given ever-increasing improvements in CT imaging quality as well as the low incidence of stent graft fractures with currently available endograft devices, the utility of radiographic follow-up is increasingly limited [38].

Nuclear Medicine

Recent research using the experimental radiotracer technetium Tc-99m–human serum albumin diethylenetriamine pentaacetic acid has shown similar sensitivity to CTA for the detection of endoleaks following endovascular repair [91]. Image quality is unaffected by the presence of streak and susceptibility artifacts related to the stent, endovascular coils, or embolization material. Furthermore, given the high labeling yield and prolonged retention in the blood pool, extraluminal accumulation of radiotracer is highly specific for endoleak. Although not likely to be a widely implemented technique, this imaging modality may be of use in patients with chronic renal insufficiency or suspected slow-filling endoleaks or in cases where prior endoleak embolization material causes prohibitive artifact on CTA.

Summary of Recommendations

- TEVAR can be successfully used to treat a wide variety of acute and chronic thoracic aorta pathologies. Imaging in the preintervention and postintervention period is critical for surgical planning and evaluation of complications.
- In the planning stage of TEVAR, CTA is the imaging modality of choice for assessment of thoracic aortic pathology and complications, given its superior accuracy. CE-MRA is an acceptable alternative in stable patients.
- Lifelong imaging follow-up is necessary in TEVAR patients as endoleaks may develop at any time. The exact surveillance interval is unclear and may be procedure and patient specific.
- In the postintervention follow-up evaluation, CTA is the imaging modality of choice, given its sensitivity for the detection of endoleaks, changes in aortic/aneurysm diameter, evaluation of false lumen thrombosis, and

assessment for device migration and integrity. MRA can provide equivalent information and is preferred for long-term follow-up of younger patients given the lack of ionizing radiation, but it can be used only with MR-compatible stent grafts.

Summary of Evidence

Of the 92 references cited in the *ACR Appropriateness Criteria® Thoracic Aorta Interventional Planning and Follow-up* document, 59 are categorized as therapeutic references including 3 well-designed studies, 30 good-quality studies, and 1 quality study that may have design limitations. Additionally, 33 references are categorized as diagnostic references including 1 well-designed study, 3 good-quality studies, and 8 quality studies that may have design limitations. There are 44 references (including 19 diagnostic references and 25 therapeutic references) that may not be useful as primary evidence.

The 92 references cited in the *ACR Appropriateness Criteria® Thoracic Aorta Interventional Planning and Follow-up* document were published from 2003 to 2017.

Although there are references that report on studies with design limitations, 37 well-designed or good-quality studies provide good evidence.

Relative Radiation Level Information

Potential adverse health effects associated with radiation exposure are an important factor to consider when selecting the appropriate imaging procedure. Because there is a wide range of radiation exposures associated with different diagnostic procedures, a relative radiation level (RRL) indication has been included for each imaging examination. The RRLs are based on effective dose, which is a radiation dose quantity that is used to estimate population total radiation risk associated with an imaging procedure. Patients in the pediatric age group are at inherently higher risk from exposure, both because of organ sensitivity and longer life expectancy (relevant to the long latency that appears to accompany radiation exposure). For these reasons, the RRL dose estimate ranges for pediatric examinations are lower as compared to those specified for adults (see Table below). Additional information regarding radiation dose assessment for imaging examinations can be found in the ACR Appropriateness Criteria® Radiation Dose Assessment Introduction document [92].

Relative Radiation Level Designations		
Relative Radiation Level*	**Adult Effective Dose Estimate Range**	**Pediatric Effective Dose Estimate Range**
O	0 mSv	0 mSv
☢	<0.1 mSv	<0.03 mSv
☢☢	0.1-1 mSv	0.03-0.3 mSv
☢☢☢	1-10 mSv	0.3-3 mSv
☢☢☢☢	10-30 mSv	3-10 mSv
☢☢☢☢☢	30-100 mSv	10-30 mSv
*RRL assignments for some of the examinations cannot be made, because the actual patient doses in these procedures vary as a function of a number of factors (eg, region of the body exposed to ionizing radiation, the imaging guidance that is used). The RRLs for these examinations are designated as "Varies".		

Supporting Documents

For additional information on the Appropriateness Criteria methodology and other supporting documents go to www.acr.org/ac.

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